SMART STRUCTURES TECHNOLOGY: INNOVATIONS AND APPLICATIONS TO ROTORCRAFT SYSTEMS

Final Report to the Army Research Office
Contract No. DAAL03-92-G-0121
"Smart Structures URI"

Period: 1 January 1992 to 31 December 1997

Department of Aerospace Engineering
University of Maryland
College Park, Maryland 20742

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13. ABSTRACT
The status of a number of rotorcraft research tasks supported under the Army Research Office "Smart Structures URI" program is reported herein for the reporting period from 1 January 1992 to 31 December 1997. For each task, the task objectives, the approach taken, and the final status of the research, and pertinent abstracts of journal articles or conference papers published as result of the research conducted under the task. Copies of all journal papers and conference papers that were produced under this program were forwarded to the U.S. Army Research Office in 1998, at the completion of the program, and are available upon request. The tasks are varied and cover many aspects of smart helicopter rotor development at the University of Maryland, including: (1) Development of a smart rotor using trailing edge flaps, and a controllable twist rotor blade, (2) Active tuning of composite shaft using shape memory alloy wires, (3) Active/passive damping for helicopter rotor satbilioty augmentation, (4) Rotor acoustics control and analysis, (5) Health monitoring and damage detection, (6) Elements of smart structures.

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Smart Structures Technology: Innovations and Applications to Rotorcraft Systems

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Period: 1 January 1992 to 31 December 1997

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For each task, the task objectives, the approach taken, and the final status of the research, and pertinent abstracts of journal articles or conference papers published as result of the research conducted under the task. Copies of all journal papers and conference papers that were produced under this program were forwarded to the U.S. Army Research Office in 1998, at the completion of the program. Inquiries are encouraged on any aspect of the report, and may be addressed to the undersigned, or to the individual investigator.

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STATUS REPORT

Development of a Smart Rotor: Induced-Strain Actuation of Composite Beams and Rotor Blades with Piezoceramic Elements

Peter C. Chen and Inderjit Chopra

The objective of this research is to build an intelligent 1/8th dynamically-scaled (Froude scale) rotor with individual blade control (IBC) in order to reduce helicopter vibrations. To alter the oscillatory lift of the blade, the twist distribution along the span of the of the blade is excited at higher harmonics of the rotational speed (N, N+1 and N-1/Rev), in order to generate new unsteady airloads which cancel the hub vibration. The smart rotor blade model under development is constructed by laminating 10 mil pre-preg fiberglass cloth plies around a rigid foam core which is cured in a NACA 0012 airfoil mold (Fig. 1). The overall blade length is 26.58 inches from tip to root and the chord is 3.0 inches. To activate blade motion independently in bending and torsion and to sense blade deformations, specially shaped, 11.5 mil single-layer actuators and 23 mil dual layer actuators are embedded under the fiberglass skin in banks of discrete actuators at angles of ± 45 degrees on the top and bottom surfaces of the blade. The piezoceramic actuators are cut to dimensions of 2.0 inches in length and 0.25 inches in width to minimize transverse actuation. The dual-layer actuators are manufactured in-house by bonding two single-layer PZT's using a high-temperature cyanoacrylate (CA) adhesive. Electrical access to both layers is obtained by soldering wires to the outer surfaces and to the common electrode at the interface. A twist distribution along the blade span is achieved through in-phase excitation of the top and bottom actuators at equal potentials, while a bending distribution is achieved through out-of-phase excitation.

In the past year, efforts have been made to improve upon the existing design of the smart blades. Various rotor configurations consisting of both single and dual-layer actuators in two actuator spacing configurations were built to study the control effectiveness of the piezo actuators in rotation. The geometric parameters of these blades are listed in Table 1. The static bending and twist responses of these blades were accurately predicted by a uniform strain beam theory (maximum error of 20%). Hover tests were conducted in a two-bladed bearingless rotor configuration (Fig. 2). To assess the twist performance of the blades in rotation, miniature accelerometers were embedded in the blade tip which resolved the rotating twist amplitudes. To evaluate the ability of the smart rotors to alter the aerodynamic forces on the hub, a rotating hub balance was used to determine the change in oscillatory rotor lift due to piezo-actuation.

The rotating blade tip twist response data for various rotor collectives and excitation frequencies of three rotor configurations are listed in Table 2. At this time, maximum twist deflection amplitudes on the order of 0.7° are attainable at 900 rpm for blade with dual-layer actuators. The change in oscillatory lift measured by the hub balance for the same three rotors at 1, 2, 3, and 4/rev excitation and 4°, 6° and 8° collective at 150 volts excitation is shown in Fig. 3-5. At the operating speed of 900 rpm, the nominal rotor lift at 4°, 6° and 8° collectives were measured to be 7.3, 12.4 and 17.9 pounds, respectively. The maximum change in oscillatory lift at 150 volts rms was measured to be up to 10, 6 and 4% of the nominal rotor lift at 4°, 6° and 8° collectives, respectively, for the dual-layer actuator rotor.

Several important observations were made from the test data: (1) actuator geometric parameters have a significant effect on the structural properties, and hence the twist performance of the blades; (2) blade twist performance in static and hover modes differ due to the presence of large external loads at high rpm; (3) considerable changes in oscillatory hub loads occur due to piezo-actuated blade twist take place.

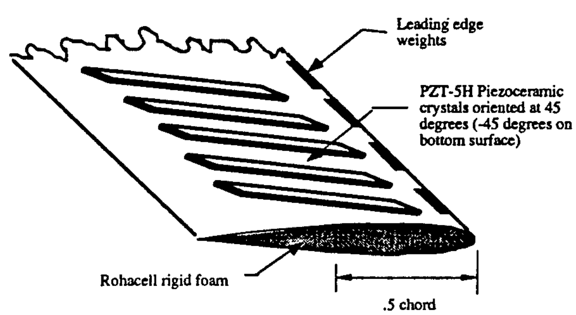
Although the blade twist amplitudes were less than that which is required for viable IBC control (on the order of 1-2°), significant improvements in the blade design have increased the twist performance of the blades by as much as a factor of two in the past year. However, at the present time, only partial vibration reduction may be feasible with the existing rotor configurations. It is expected that a smart rotor with an optimized actuator configuration may meet the performance requirements for vibration reduction application

To further investigate the vibration suppression capabilities of the smart rotor, forward flight testing is planned in the Glenn L. Martin Wind Tunnel.

Publications

1. Chopra, I. and Chen, P. C., "Update on the the Development of a Smart Rotor," *Presented at the 31st Society of Engineering Science Conference, Smart Structures and Materials Session*, University of Texas at Austin, TX, October 1994.

2. Chen, P. C. and Chopra, I., "Hover Testing of a Smart Rotor with Induced-Strain Actuation of Blade Twist," *Proceedings of the 36th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics and Materials Conference, Adaptive Structures Forum*, New Orleans, La, April 1995.



NACA 0012 Airfoil Section
Fig. 1. Piezoceramic blade cross section detail

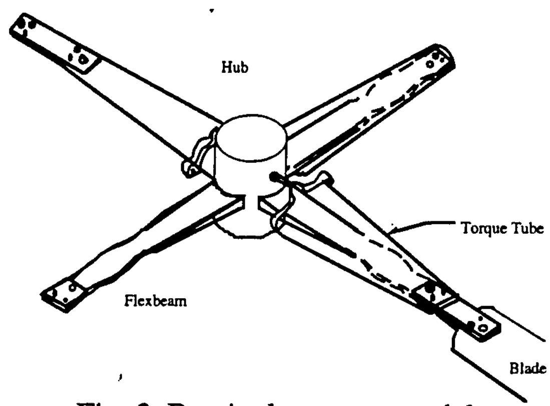


Fig. 2 Bearingless rotor model

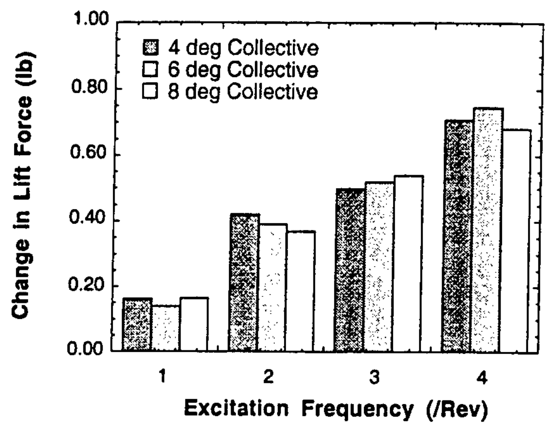


Fig. 3 Rotor 2A lift force at 150 volt rms excitation

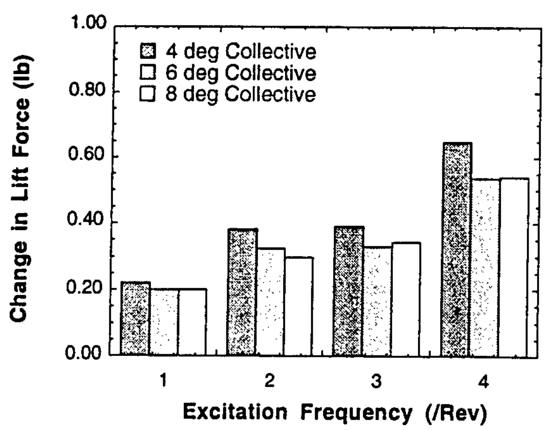


Fig. 4 Rotor 1B lift force at 150 volt rms excitation

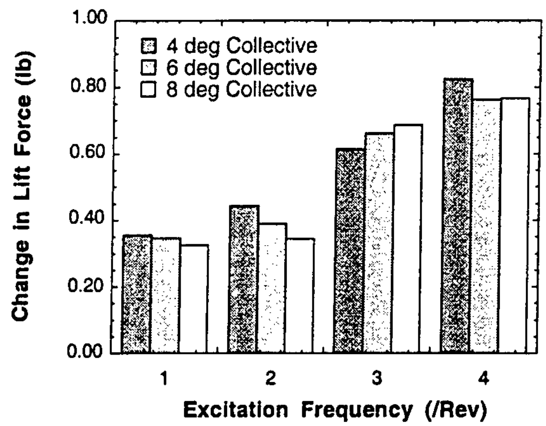


Fig. 5 Rotor 2B lift force at 150 volt rms excitation

Blade ID#	PZT Type	ΔS (inch)	Total Pairs	Active Pairs
1A1	single	1.50	12	12
1A2	single	1.50	12	12
1B1	single	0.75	30	30
1B2	single	0.75	30	30
2A1	dual	1.50	12	11
2A2	dual	1.50	12	11
2B1	dual	0.75	30	25
2B2	dual	0.75	30	24

Table 1. Rotor blade actuator configurations

Rotor ID #	1/Rev Excitation			2/Rev Excitation			3/Rev Excitation			4/Rev Excitation		
	θ_0=4	θ_0=6	θ_0=8	θ_0=4	θ_0=6	θ_0=8	θ_0=4	θ_0=6	θ_0=8	θ_0=4	θ_0=6	θ_0=8
1B	0.081	0.080	0.055	0.242	0.211	0.184	0.360	0.254	0.278	0.490	0.453	0.352
2A	0.175	0.196	0.182	0.301	0.337	0.253	0.322	0.373	0.297	0.397	0.423	0.393
2B	0.300	0.291	0.255	0.411	0.344	0.282	0.469	0.459	0.389	0.78	0.709	0.615

Table 2. Rotating blade tip twist amplitudes at 900 rpm, 150 volts rms excitation

Development of a Smart Rotor: Trailing Edge Flap Actuation with Bending-Torsion Coupled Composite Tube

Andreas P.F. Bernhard and Inderjit Chopra

Introduction

This research is aimed at the development of an individual blade control rotor system via an active trailing edge flap on the rotor blade. In this approach the flap will be activated via a composite beam with a bending-torsion coupling. The beam has surface mounted piezoceramic elements. These are used to bend the beam. As a result of the structural coupling the beam will twist.

Objectives

- Design and build a bending-torsion flap actuation beam
- Validate the induced strain actuation of the bending torsion coupling
- Validate Analytic Model
- Integrate into a 1/8 scale model rotor blade for wind-tunnel and hover-stand testing

Concept

The composite beam will be located spanwise in the blade. The flap is rigidly attached to the tip of the beam and constrained via an outboard bearing. Thus the beam twist axis is the effective flap hinge axis. A novel spanwise variation in layup is used to minimize the bending deflection, while simultaneously maintaining the full twist response.

This system effectively constitutes a "solid state flap" as it contains no mechanical hinges or moving parts. The flap deflection is achieved via induced strain actuation of a composite beam with structural couplings. The main advantage of this flap system is that it uses the entire length of the blade and that no mechanical amplification is required.

With the current performance of piezo-ceramic crystals it is estimated that a 250mm long, 25mm wide and 1mm thick beam will deliver a static twist range of 1.5 degrees for a piezoceramic voltage range of -150 to 150 V. The twist is proportional to the length of the beam. For the 1/8 scale model rotor blades a useful blade length of 560mm will allow a correspondingly sized beam to generate a peak to peak flap deflection of 3.5 degrees.

Status

Test specimens of the beams have been manufactured with varying length and thickness. The reference specimen is 250mm long, 25mm wide and 1mm thick with an effective piezo actuation length of 203mm (based on 4x2 inch surface piezos)

Static tests of the reference specimen show that for a voltage range of -100V to 100V the twist response is linear with the number of spanwise activated piezo pairs. The peak to peak response for all four piezo pairs activated is 0.9 degrees while the bending deflection is less than 10% thereof.

A model rotor blade is being constructed for integration of a 440 mm long flap actuation beam.

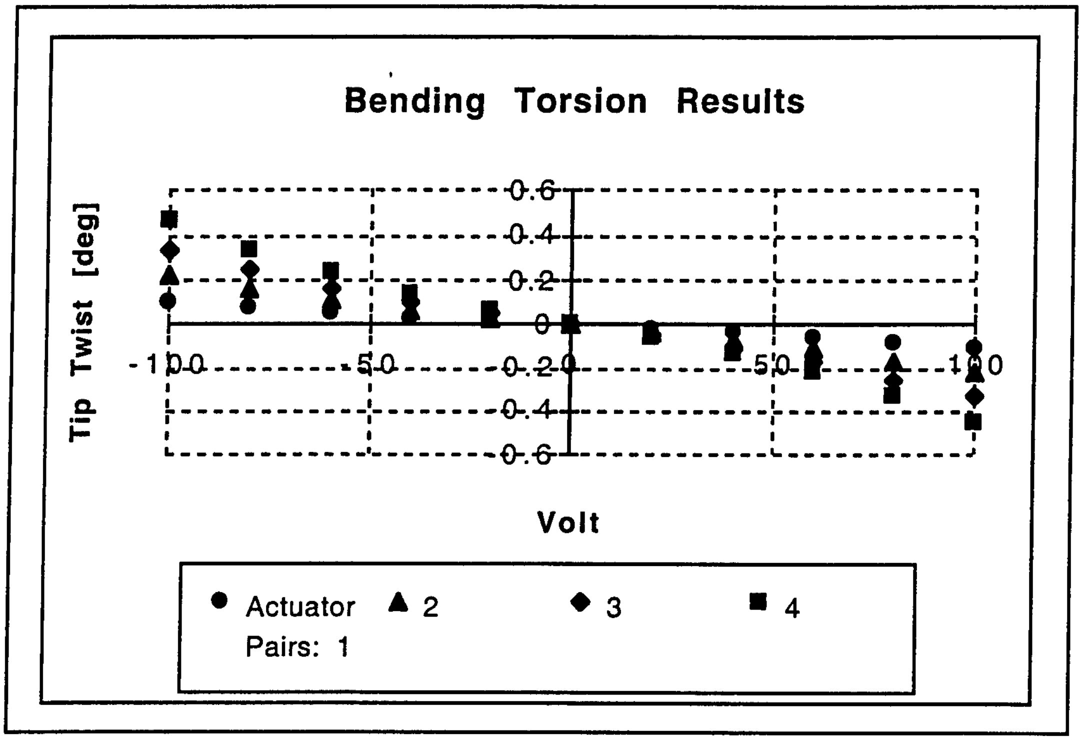


Figure 1 Analytical Bending-torsion

Development of a Smart Rotor: Design and Testing of a Helicopter Rotor Model with Smart Trailing Edge Flaps

Orren Ben-Zeev and Inderjit Chopra

Helicopters suffer from high vibration levels primarily because of the unsteady and complex aerodynamic environment in which the rotor operates. Higher Harmonic Control (HHC) systems heretofore used to reduce these vibrations incur a high weight penalty and are limited to excitation frequencies that are multiples of N/rev. In order to also minimize blade stresses and improve rotor performance, attention has been directed toward the development of Individual Blade Control (IBC) systems, which can control the pitch of each blade independently and at any desired frequency. A very promising approach to IBC that is being explored in the current research is lift-control of the blade using a trailing-edge flap powered by an induced strain actuator. The actuator is a bimorph bender element consisting of piezoceramic (PZT) sheets diametrically bonded to a thin brass shim with a conducting adhesive. The bimorph is cantilevered at one end and opposite voltage fields are applied to the PZT sheets, inducing the bimorph to bend, and the tip displacement provides the actuation mechanism. The bimorph actuator is light-weight and compact, making it ideal for IBC purposes.

One of the objectives of the present work was to experimentally verify the static performance of both 2 and 4 layer bimorph actuators and compare the results with the predictions of two analytical models, a modified Uniform Strain model and a Bernoulli-Euler model. This undertaking indirectly prompted a look into improving the technique used for fabrication of 4 layer bimorph elements, whose high block force makes them more attractive for use in this application. Static tests were conducted to verify the structural rigidity of the actuators (Fig. 1), as well as the tip displacement induced by an applied DC voltage. In summary, the tests showed that the analytical models used over-predicted the displacement for both the 2 and 4 layer case, implying that a model more suitable for low beam/actuator thickness ratios is needed to better represent bimorph behavior.

Tests were also performed to ascertain the dynamic response of both the actuator alone as well as the actuator linked to the flap assembly. A comparison of the results for each case showed that along with the substantial reduction of the resonance frequency for the actuator-flap case, the resonance amplitude for this system decreased sharply, indicating a high amount of frictional damping present in the mechanical amplification arrangement (Fig. 2). To increase the efficiency of energy transfer between the bimorph and flap, a better linkage between the two is required.

New 1/8 Froude-Scale blade models forming a rotor of 6 foot diameter were constructed and tested in a vacuum chamber to isolate the effects of centrifugal loading on the actuator-flap system. Tests with both 2 and 4 layer actuators were performed. Results from a vacuum test with a 4 layer bimorph (Fig. 3) show that the flap exhibited similar behavior even in the absence of all aerodynamic forces, and that deflections of only 0.5 degrees were obtained.

An analytical model of the forces acting on the flap and actuator assembly in a rotating environment was developed to determine the effects of centrifugal loading on the bimorph tip displacement. The centrifugal loads were integrated into the boundary conditions used for calculating the displacement of the actuator under a statically applied voltage field. The first load considered was the propeller moment acting at the bimorph clamp, generated by the chordwise component of the centrifugal force on any discretized bimorph element. This propeller moment can also be expressed as a span-varying axial load T(x). The second load considered was the propeller moment created about the flap hinge by the flap deflection. This moment could be directly translated into a shearing force F acting at the bimorph tip. The bimorph can be represented as a cantilevered beam and is acted upon by these loads, as shown in Fig. 4. A Rayleigh-Ritz analysis was carried out to obtain the resulting tip deflection. It was found that at 900 RPM, the tip displacement was reduced by approximately 14%, not enough to explain the poor behavior of the flap at high rotor speeds.

It was then hypothesized that the governing phenomenon affecting the flap in a rotating environment was the friction created at the junction where the hinge axis tubes for the blade and flap coincide. This friction is caused by the relative motion between the rotating and non-rotating parts, and at high rotational speeds may be quite substantial compared to the total actuation force available. Any inexact positioning of the two hinge tubes can be a source of greater friction and may even cause elastic deformation of one or both tubes, especially at the higher rotor speeds. To partially alleviate this problem, a tiny machined stainless steel thrust bearing was mounted on the blade at this junction, as shown in Fig. 5. Since the outer diameter of the bearing is greater than that of the tube, this arrangement alleviated the consequences of misalignment of the two tubes and eliminated any elastic deformation.

Subsequent vacuum test results obtained with a 4 layer bimorph showed marked improvement at higher rotor speeds, as deflections of 10 degrees peak-to-peak were achieved at 800 RPM (Fig. 6). Initial tests performed on the bearingless hover stand at a conservative voltage level of 90 Volts RMS showed that deflections of 4 degrees peak-to-peak can be obtained at 750 RPM. It is expected that future tests performed at higher voltage levels using a biased sinusoidal excitation signal will yield even greater deflections.

Publications

[1] O. Ben-Zeev and I. Chopra, "Continued Development of a Helicopter Rotor Model Employing Smart Trailing-Edge Flaps for Vibration Suppression", *Proceedings of the SPIE North American Conference on Smart Structures and Materials*, San Diego, CA, 27 Feb - 3 Mar, 1995.

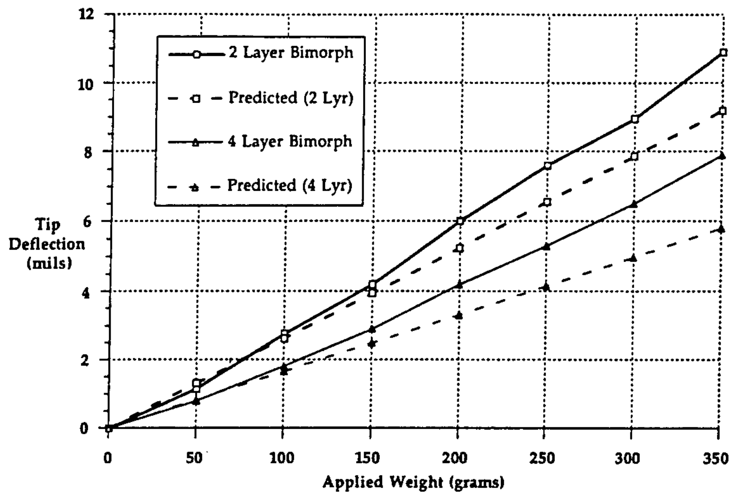
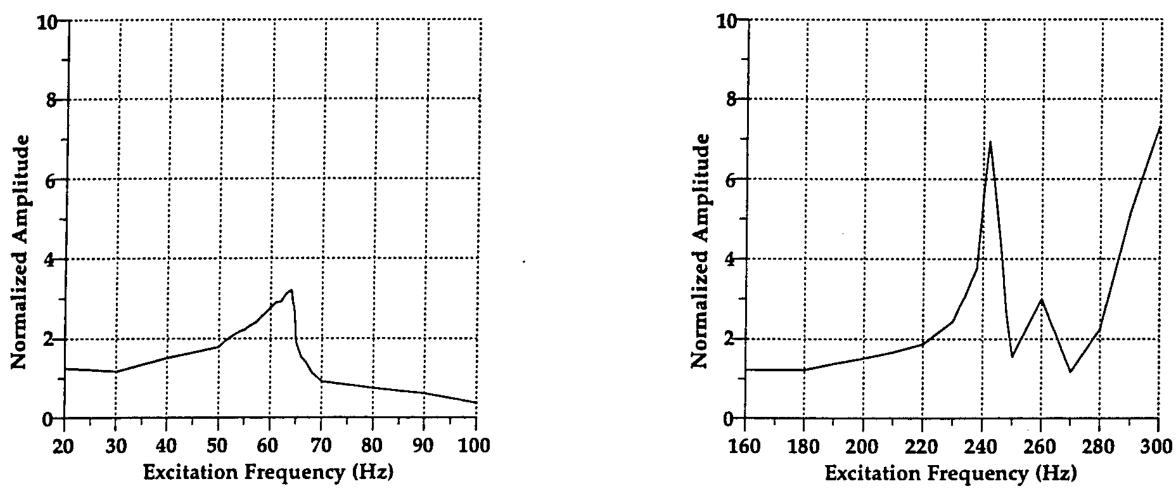


Figure 1: Stiffness Test for 2 and 4 Layer Bimorphs



Actuator Alone

Actuator Flap Assembly

Figure 2: Frequency Response Test

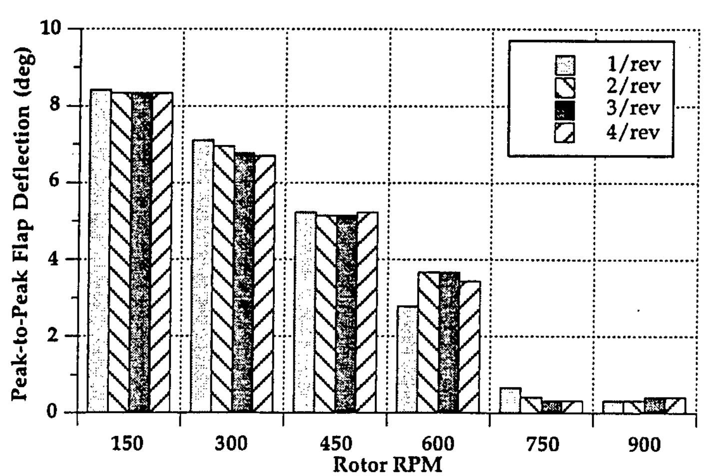


Figure 3: Vacuum Chamber Test - 4 Layer Bimorph

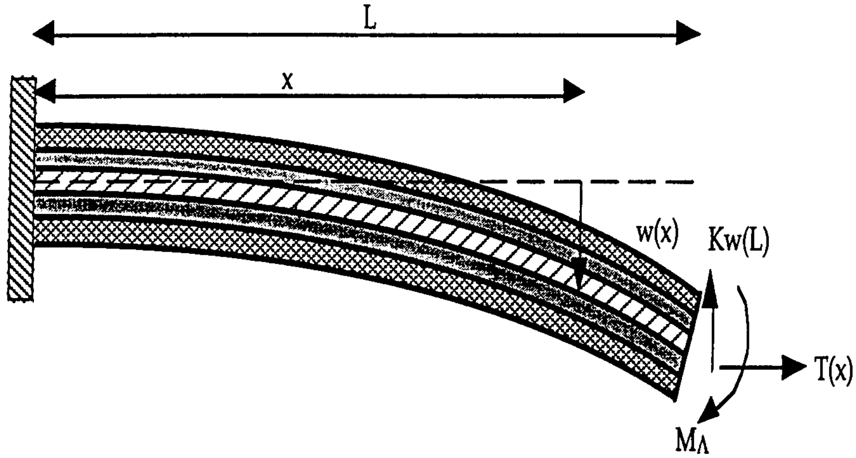


Figure 4: Propeller and Induced Exerted as Loads on Bimorph Tip

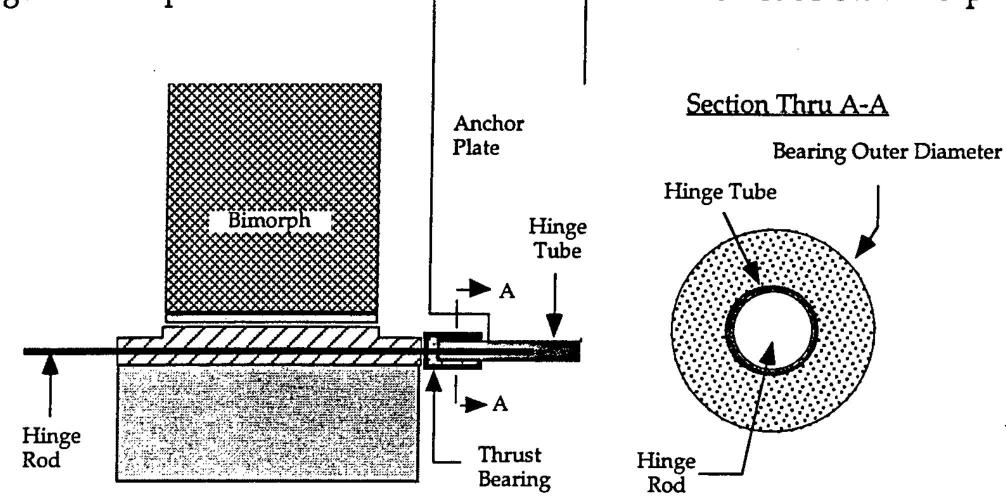


Figure 5: Bimorph-Flap Assembly with Thrust Bearing

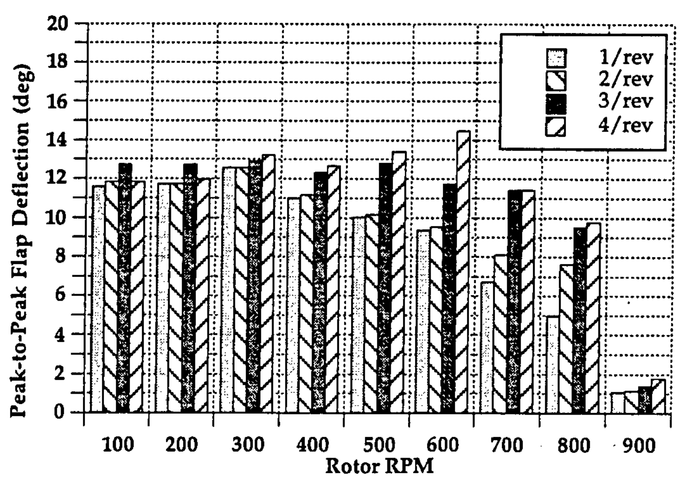


Figure 6: Vacuum Test - 4 Layer Bimorph with Thrust Bearing

Development of a Smart Rotor: Design and Testing of a Trailing Edge Flap Using Piezoelectric Stacks

Burtis Spencer and Inderjit Chopra

Modern helicopters suffer from vibration induced problems such as high fatigue loads, excessive noise, and large vibrations felt by the crew and equipment on board the helicopter. Research has shown that individual blade control (IBC) systems can substantially reduce vibration by eliminating it at its source, namely the rotor disk. In this research, a trailing edge flap powered by piezoelectric stacks is being studied as an IBC device.

The piezoelectric stacks being used in this project are .44 inch square by .72 inch in length. Two individual stacks with a free displacement of .75 mil each have been bonded together in a series configuration which results in an effective stack of 1.44 inch having a free displacement of 1.5 mil. The block force of the series configuration will remain equal to that of a single stack, namely 1445 lb.

One of the fundamental problems in using piezo stacks is that due to their construction, the stacks can withstand compressive loads only. Any type of shear or tensile load will cause the mechanical failure of the stack. This becomes a major issue when designing an actuator for use in a rotor blade with the inherently high centrifugal loads. In this design, the stacks are placed with their axes parallel to the quarter chord line with the outboard end in a fixed restraint such that the centrifugal loading produces a compressive load only in the stack.

The low free displacement of the stacks requires the use of large mechanical amplification factors to achieve a usable displacement. his amplification is achieved via the use of an L-arm. The current design uses a L-arm with a magnification factor of 10 to operate a push rod. The push rod in turn actuates the flap through an offset hinge arrangement as shown in Figures 1 and 2.

At the present time, construction has just been finished on a model that consists of an 8 inch chord, NACA 0012 airfoil with a span of 8.6 inch. The model incorporates a trailing edge flap with a 20% chord ratio and 4 inch span. The testing of this model will be done in three stages. The first stage will consist of measuring flap deflections in a static environment with both DC and AC inputs. Then, the flap performance will be tested in wind tunnel using a non rotating (fixed wing) configuration. These tests will be compared to the static performance to determine what effects aerodynamic forces have on the flap performance. The third set of tests will consist of operating the flap with the model in a rotating environment in the University of Maryland vacuum chamber. These will results will also be compared with the static tests to determine the effects of centrifugal forces on the flap.

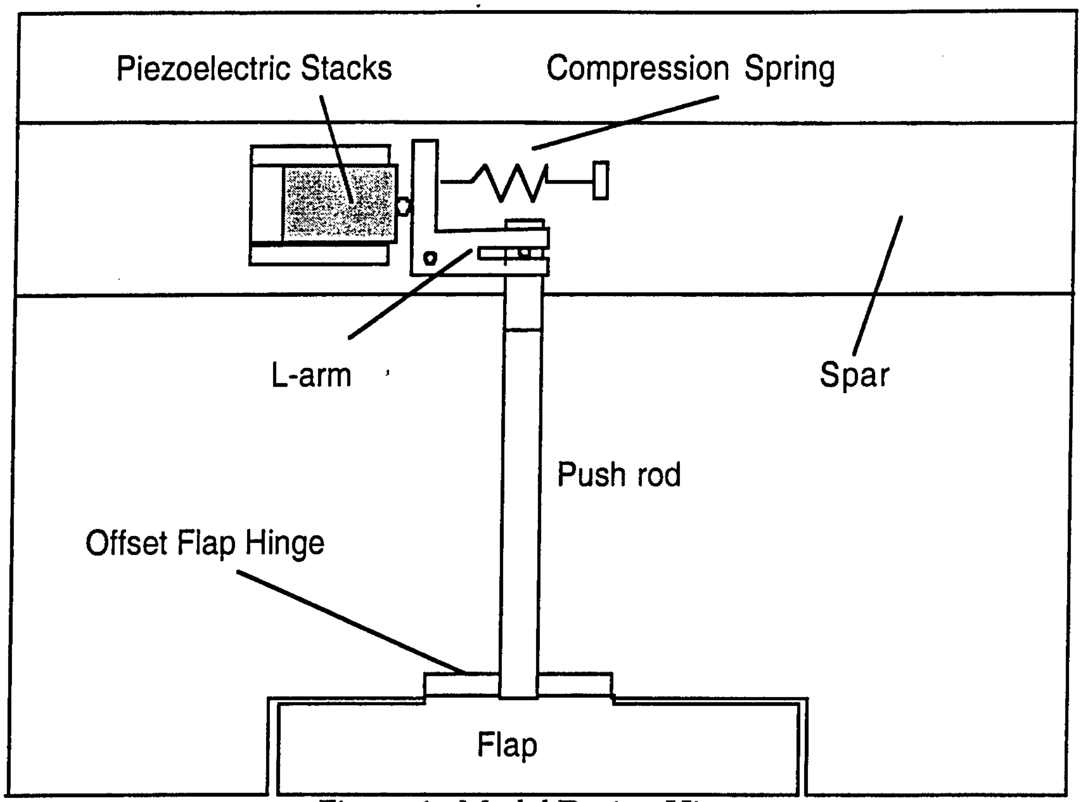


Figure 1. Model Design Hinge

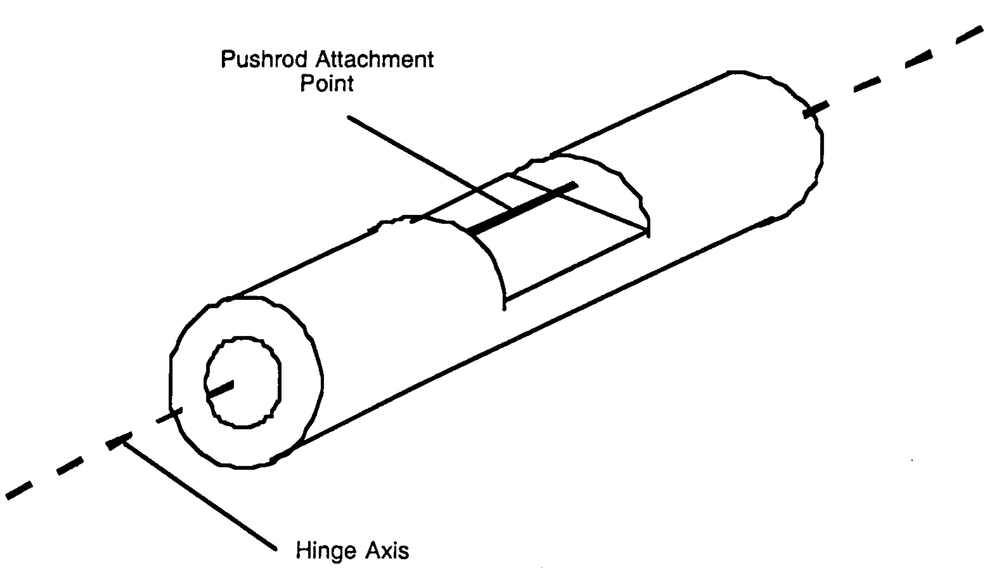


Figure 2. Offset Flap

Development of a Smart Rotor: Active Tuning of Composite Beams Using Shape Memory Alloy

Janette Epps and Ramesh Chandra

Conventional shafts for power transmission to the tail rotor in helicopters have a subcritical design, that is, the operational rotating speed is lower than the first natural frequency of the shaft. Lighter shafts are possible by employing supercritical design wherein the operational speed is higher than the critical speed. However studies have shown a need to reduce the response of the supercritical shaft when it's going through resonance and balancing problems were identified. Some of these problems could be alleviated using active tuning of the shaft with shape memory alloy (SMA) actuators. As a first phase of smart composite shaft problem, the active tuning of a simple composite beam is addressed in this investigation.

The objective of this research is to actively tune composites beams using Shape Memory Alloy (SMA) wires. Composite beams with fused silica tubes and dummy wires were manufactured first using autoclave molding technique and the dummy wires were replaced by pre-strained SMA wires. These beams with SMA wires were tested at different temperatures for their natural frequencies and the increase in frequency due to phase transformation from martensite to austenite in SMA wires was determined. Analytically, these beams with SMA wires inserted in embedded sleeves were examined as beams on an elastic foundation: the spring constant of the elastic foundation depended on the axial recovery force of SMA wire. Good correlation between analysis and experiment was achieved. A numerical parametric study of natural frequencies of composite beams with activated SMA wires was conducted. The parameters considered were diameter and number of SMA wires and material of composite beam.

Experiments

Although there have been many studies on the testing of free SMA wire, there is still a need to test the wire prior to use. This need exist because a suitable analysis for predicting properties such as the recovery force does not exist. Therefore in this study the recovery force in activated SMA wire was experimentally determined.

The composite beams with fused silica tubes filled with dummy steel wires were fabricated using an autoclave molding technique. After curing the composite beam, the steel wires were replaced with pre-strained SMA wires. The composite beams were then tested for their bending frequencies under clamped-clamped boundary conditions. Two piezoceramic bending elements were used to excite the composite beams with sleeves. Strain gages located on the piezo actuators and the beam surface were used to measure the structural response.

Analysis

The composite beam with SMA wires inserted in sleeves was modeled as a beam on an elastic foundation. Using Galerkin's method, the frequency of the beam with SMA wires is obtained as:

$$\omega_i = \sqrt{\left[\frac{EI}{m}\left(\frac{\lambda_i}{l}\right)^4 + \frac{I_{ii}}{m\,l}\right]}$$

where,

$$I_{ii} = \int_0^l \kappa(x)\, \phi_i^2 \, dx,$$

and $\kappa(x)$ is the stiffness of the elastic foundation.

Results

Figure 1 shows the first bending frequency of a graphite-epoxy composite beam activated by one 20 mil diameter SMA wire. The increase in the fundamental frequency due to 100% SMA activation (temperature= 160°F) is 21.8%. The correlation between theory and experiment is within 5%.

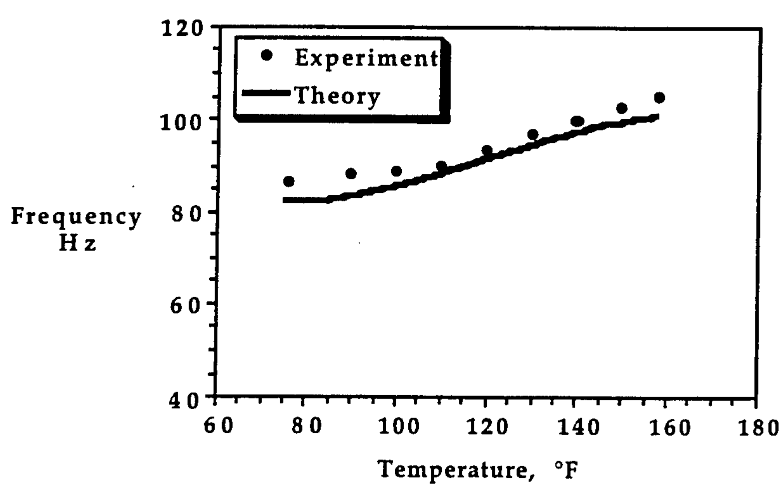


Figure 1. Fundamental frequency of clamped-clamped graphite-epoxy beam activated by one 20 mil diameter SMA wire, beam dimension

Figure 2 shows the predicted fundamental frequency of a graphite-epoxy beam actuated by multiple 20 mil diameter SMA wires. The clamped-clamped beam dimensions are length=30 inches, width = 1 inch, and thickness = 62.5 mils. The increase in the frequency using 25 wires of 20 mil diameter is 276%. Note that it is feasible to insert 25 wires of 20 mil diameter into a 1.0 inch beam.

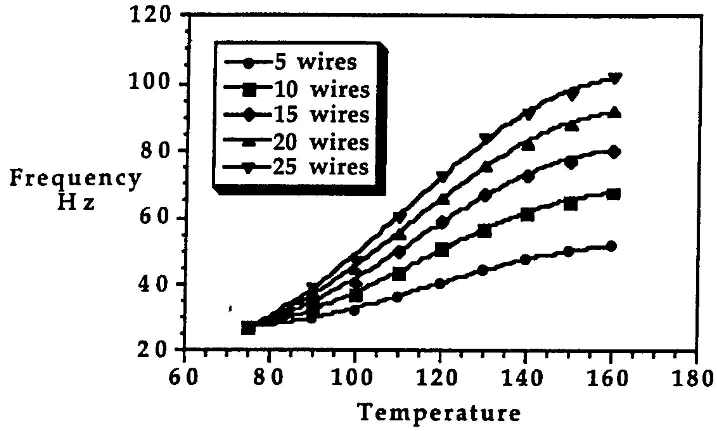


Figure 2. Fundamental frequency of clamped-clamped graphite-epoxy beam activated by number of 20 mil diameter SMA wires, beam dimensions

Conclusions

The active tuning of composite beams using shape memory alloy (SMA) wire actuators is examined experimentally and analytically. The SMA wires are inserted in the sleeves which are embedded in graphite-epoxy beams during their manufacturing. Based on this study the following conclusions are drawn:

1. One 20 mil diameter wire inserted into a graphite-epoxy composite beam with sleeves increases its first frequency by about 22%. The correlation between theory and experiment for this case is within 5.1% .

2. Numerical studies suggest that it is feasible to obtain a substantial increase in the frequency of composite beams by using multiple SMA wires. A 276% increase in the frequency is obtained by using 25 wires of 20 mil diameter.

Publications

J. Epps and and R. Chandra (1995). "Shape Memory Alloy Actuation for Active Tuning of Composite Beam," To appear in *1995 SPIE Conf. on Smart Structures and Materials*, Feb. 26 - Mar. 3, 1995, San Diego, CA.

Active/Passive Damping for Stability Augmentation

Norman M. Wereley

In this task, the issue of stability augmentation in hingeless and bearingless rotors is the key motivating problem. The perspective taken here is to augment the mechanical damping of the flexbeam in these advanced rotors through application of smart structures technology. Several strategies are currently being explored for effecting this improvement in flex beam damping including: distributed damping and point damping using electro-rheological fluids and magneto-rheological fluids, passive and active constrained layer damping using visco-elastic and piezo-ceramics. Models have been developed for each of these strategies that would be useful in both dynamic analyses and in the design of feedback or feedforward controllers.

A new research thrust has been initiated in collaboration with Dr. Balachandran of the Dept. of Mechanical Engineering to examine the benefits of smart composites in the control of interior acoustics.

Each of these tasks is described below.

Design of Point Dampers using ER Fluids

Gopalakrishna M. Kamath, Melanie Hurt and Norman M. Wereley

A numerical study of electrorheological (ER) dampers is presented. Two models, the Newtonian and the Bingham plastic models are used to characterize the ER fluid behavior. Damping performance of two damper configurations, the Moving Electrode and the Fixed Electrode configurations, is studied. The effects of electrode gap sizes, the field strength and the ER fluid model used are quantified. The study provides a basis for design of ER-fluid based dampers.

A comprehensive study involving different ER fluid models and damper configurations is currently lacking in the literature. The study presented here provides a basis wherein the design of ER-fluid based dampers is possible. Two electrode configurations are considered. These configurations are representative and can be easily extended to other configurations. Fluid inertia effects are not significant for low frequency applications and hence are ignored in this study. The relevant equations are presented for the Bingham plastic model and Newtonian model. The latter is presented for its simplicity and can be used to obtain fairly accurate results for low fields.

The two damper configurations studied in this paper are shown in Fig. 1. Fig. 1(a) shows the Moving Electrode configuration. This is essentially a piston type of damper with the piston being one of the two electrodes. The other electrode is the outer casing of the damper. Thus the properties of the fluid between the piston and the casing can be controlled by suitable application of an electric field. The sources of damping in this configuration are the viscous drag of the piston and the pressure drop along the length of the electrodes. Fig. 1(b) shows the Fixed Electrode configuration. In this case, both the electrodes are fixed and the piston drives the fluid between the electrodes. The damping source here is solely due to the pressure drop along the electrodes. This configuration has the advantage of having the two electrodes separated from the damper setup using a by-pass valve. This helps in isolating the high voltage hardware from the main damper.

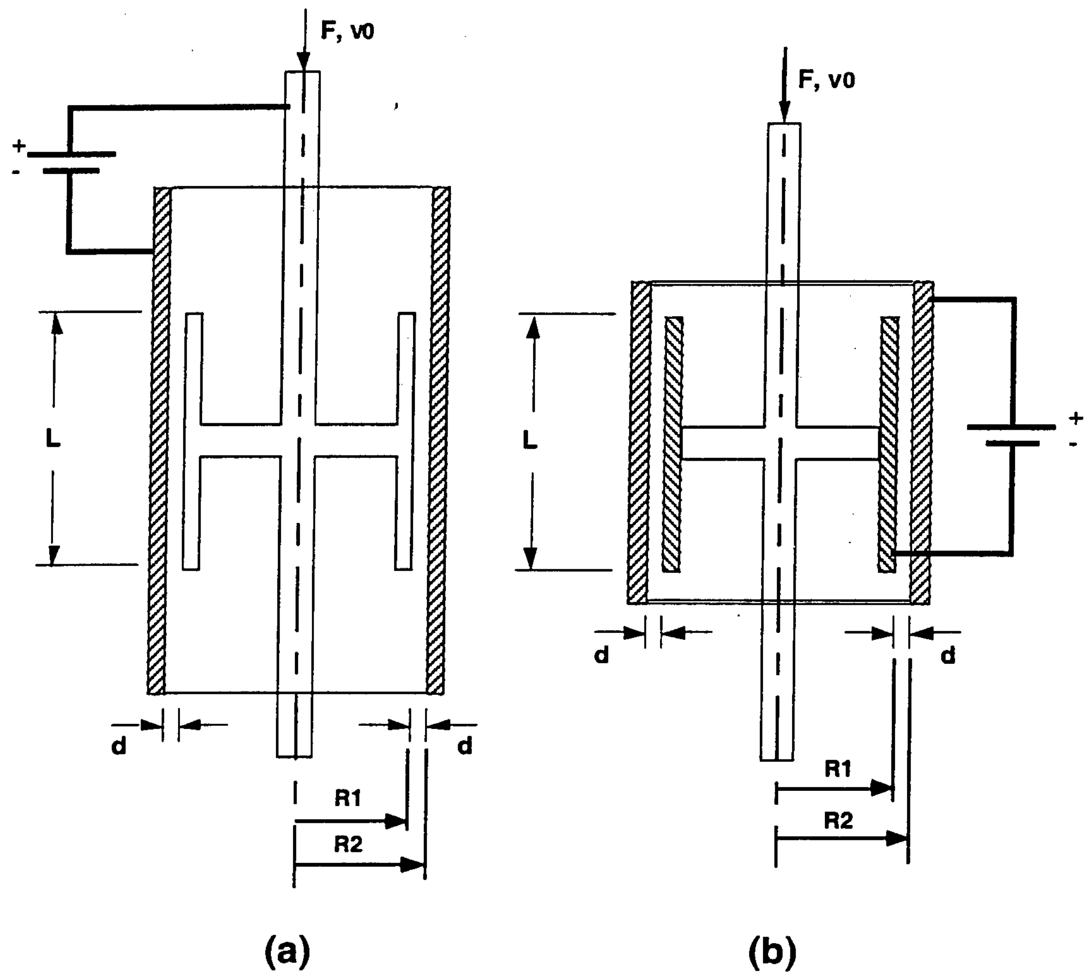


Figure 1: ER fluid damper configurations. (a) Moving electrode damper configuration. (b) Fixed electrode damper configuration

The viscous damping parameter, c, which is proportional to the velocity is to be calculated for both of these configurations. These analyses are complete for both a Newtonian viscous shear law, and for a Bingham plastic shear law. In both of these cases, quasi-steady flow was assumed. In other words, the force applied to the damper was constant and neither oscillatory nor periodic, so that fluid inertia terms were ignored. The Newtonian viscous shear law was used to derive the damping parameter for both the moving and fixed electrode configurations. These results are available in detail in [Kam95a].

The Bingham plastic shear law was used to calculate the equivalent viscous damping for the fixed electrode damper. This result is shown in Figure 2 for two different loadings, 800 and 1500 N. Based on this calculation, an interesting conclusion is that increasing the force reduces the adaptability of the damping constant as the electric field is changed.

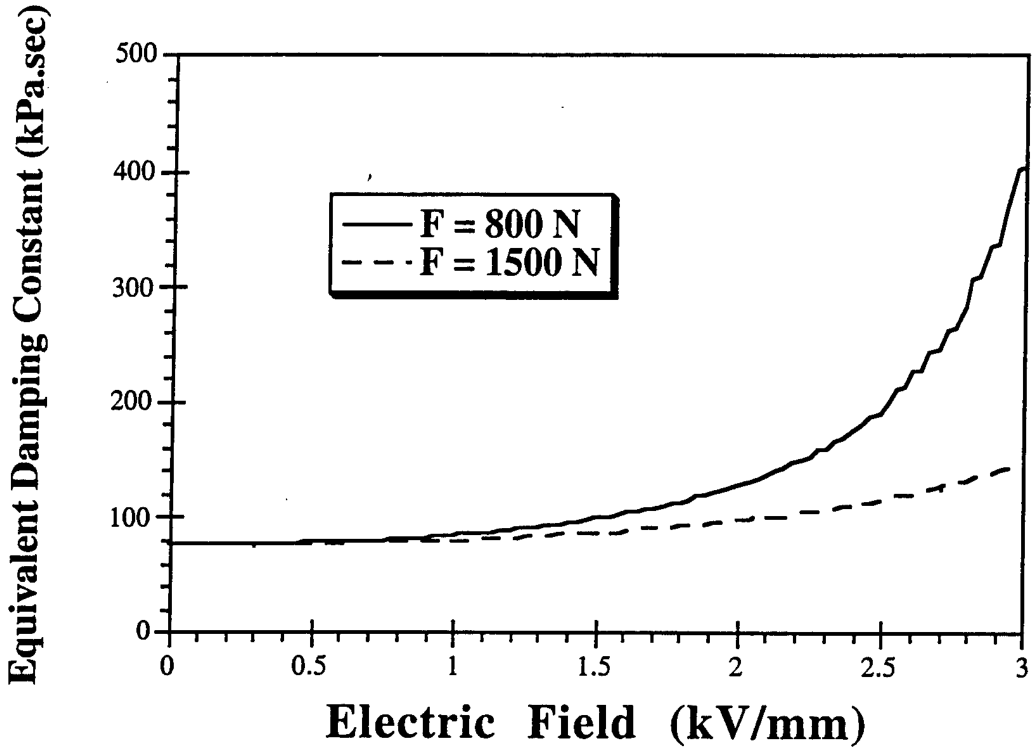


Figure 2 The Bingham plastic shear law was used to calculate the equivalent viscous damping for the fixed electrode damper. The damping parameter, c, is shown for two different loadings, 800 and 1500 N.

Future work will seek to conclude the analysis for ER fluid-based dampers using a Bingham plastic shear law for both the fixed and moving electrode configurations, as well as other dampers. The same models will be used to develop magnetorheological fluid-based damper equations and analyses. ER and MR fluids will be compared in terms of their performance for a lag damper application in a hingeless/bearingless rotor.

A paper was presented on this topic at the 1995 SPIE Smart Structure and Materials Conference.

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[Kam95a] G.M. Kamath, and N.M. Wereley (1995). "Development of ER fluid based actuators for rotorcraft flex beam applications." To appear. *SPIE 1995 North American Conference on Smart Structures and Materials: Smart Structures and Integrated Systems.* SPIE Paper No. 2443-13.

Nonlinear Viscoelastic / Plastic Model for ER Fluids

Gopalakrishna M. Kamath and Norman M. Wereley

Controllable fluids such as electro-rheological (ER) and magneto-rheological (MR) fluids are candidates for active damping and stability augmentation of the lag mode in advanced rotor systems which suffer from aeromechanical instabilities such as air and ground resonance. ER fluids are colloidal suspensions that exhibit dramatic reversible changes in properties when acted upon by an electric field. ER fluids demonstrate significant increases in shear yield stress and viscosity when an external electric field is applied. This pseudo-phase change can be reversed within milliseconds.

A large number of representations and models for ER fluid behavior exist in the literature. Most of them deal with a single dimension involving the shear stress, shear strain or the shear strain rate. Experimental studies have shown that ER materials behave differently in different domains and for varying electric fields. However, the existing models in the literature have failed to incorporate these effects. A nonlinear model was developed that effectively combined two simple linear models using non-linear functions to describe ER fluid behavior. The results showed that the non-linear effects in the hysteresis loops are very well simulated using this model.

Viscoelastic-Plastic Model

Two dominant characteristics govern the ER fluid behavior: the viscous and the viscoelastic models. The viscous element is represented by a simple dashpot and the viscoelastic behavior is represented by a 3-parameter fluid element shown in Figure 1. When the strain rate is below the yield point, the ER material exhibits viscoelastic behavior. At strain rates above the yield point it tends to flow with viscous properties. These two characteristics can be combined using shape functions to produce the above effect. The shape functions used in this model are shown in Figure 2. S_1 represents the viscoelastic behavior with its value changing from unity below the yield point (in this case, 0.5) to zero above the yield point. S_2 represents the viscous characteristics and follows the inverse pattern as S_1. The two models and the two shape functions can then be combined into a single model whose schematic is shown in Figure 3. L_1 and L_2 are the linear differential operators denoting the viscoelastic and viscous models respectively. The data presented by Gamota and Filisko [Gam91] is taken as the basis for the model parameter estimation. The parameters to be determined are the viscoelastic parameters C_1, C_2 and K_1 and the viscous parameter μ. Using the parameters estimated from the optimization process, the hysteresis loops are reconstructed and compared with the experimental data. These are shown in Figure 4. Figures 4(a) and 4(b) represent the hysteresis characteristics at fields of 0 kV/mm and 1 kV/mm which are the linear viscous and viscoelastic models respectively. Figures 4(c) and 4(d) are the plots for 2 kV/mm and 3 kV/mm field strengths respectively and represent the non-linear effects at high fields. The figures show that the model accurately captures the ER effects including the nonlinearities. The E = 3 kV/mm plot in

Figure 4(d) represents a behavior which is similar to that of a Coulomb friction model. Thus this analysis brings to light an important conclusion that what appears to be a Coulomb friction (or Bingham plastic) behavior is a combination of two linear characteristics separated by a yield region.

Future Work

More experimentation needs to be done to further improve the model so as to include the effects of strain amplitude and frequency. The fluid model has to then be incorporated into a comprehensive damper analysis to be able to predict the dynamic behavior of ER fluid-based dampers. The damper model can then be included into a rotor code and a control strategy developed to augment damping for air and ground resonance problems.

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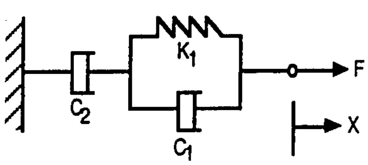

Figure 1. The 3-parameter viscoelastic fluid model

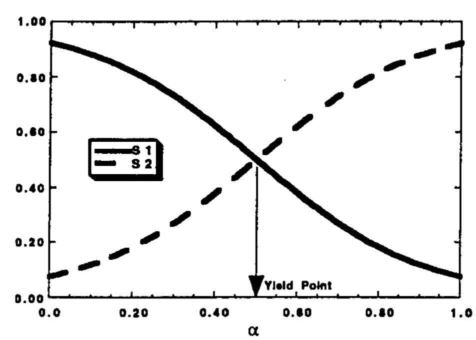

Figure 2. Shape functions as a function of strain rate, α. $\alpha_y = 0.5$

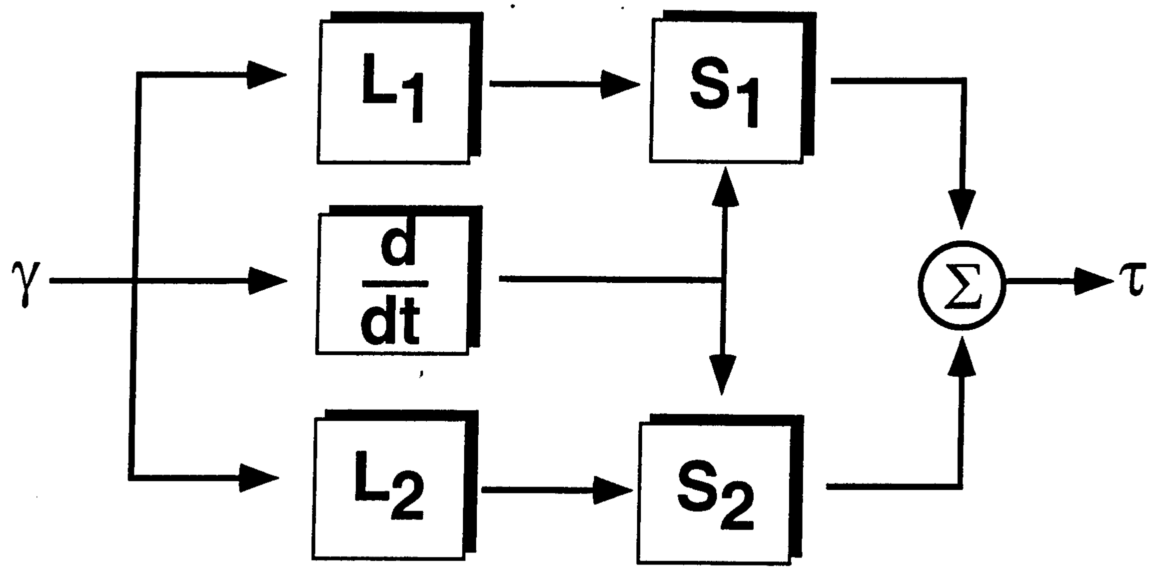

Figure 3. Schematic of proposed mechanisms-based model. L1 is a 3 parameter visco-elastic fluid element, and L2 is a viscous fluid element. The linear shear output of these two elements is combined using nonlinear shape functions in order to develop accurate representation of the nonlinear ER fluid behavior.

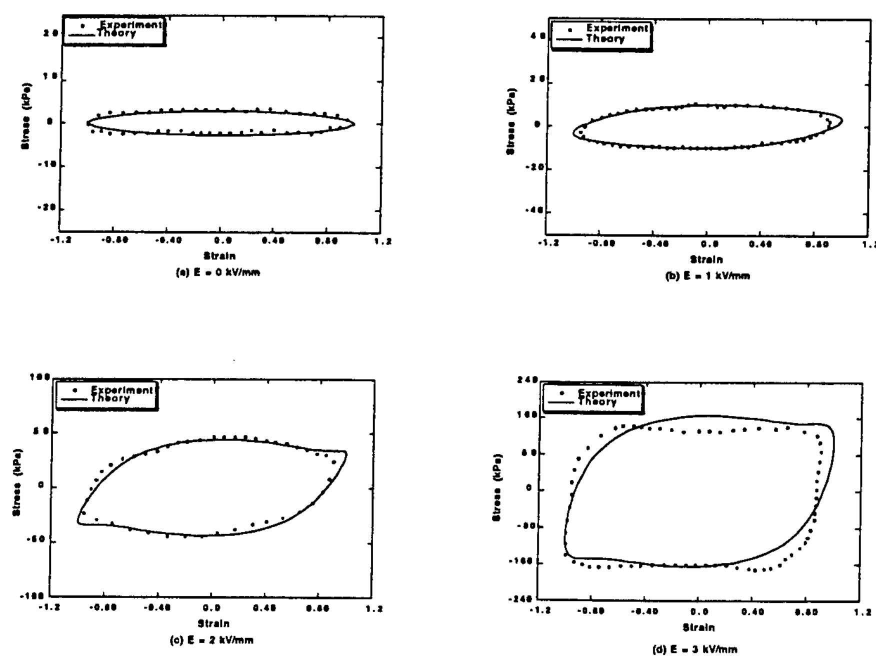

Figure 4. Hysteresis plots for different field strengths

Passive Damping for Composite Rotorcraft Flexbeams

Clifford Smith and Norman M. Wereley

Passive damping can be accomplished several ways, including dashpots and damping films. The concept of damping films involves adding layers of viscoelastic material in or on the flexbeam is such a way as to increase the damping of the flexbeam. Unlike active systems, passive damping does not require any type of electronic control system in order to be effective. It is the concept of damping films which is the subject of this research

Complex cross-sections such as I-beams, tubes (circular and rectangular), and cruciform cross-sections are candidates for use in rotorcraft applications. Chandra and Chopra [Chan93] have studied the dynamic characteristics of composite I-beams for application to a rotorcraft flexbeam, so this geometry was chosen for further damping analysis. The use of composite materials allows for great manufacturing flexibility of parameters such as viscoelastic location and ply orientation. Unfortunately, these composite I-beams have lower inherent damping than I-beams manufactured from traditional materials. This need for increased damping may possibly be met by including viscoelastic layers within the I-beam. Figure 1a shows the I-beam layup configuration used in [Chan93] which will be used as a baseline, and Figure 1b shows an example of the I-beam configurations incorporating viscoelastic layers that are being investigated.

Experimental Work

In order to better understand the mechanisms affecting the damping of composite I-beams with integral damping layers, an experimental program was initiated. Fabrication of several graphite/epoxy I-beams is complete, and dynamic testing of each beam is currently underway. The testing will consist of both non-rotating and rotating conditions in the vacuum chamber at the University of Maryland, including characterization of modal damping and frequency properties. In order to collect the data necessary to determine the damping of each beam, two piezo crystals are mounted at the root of each beam, one on the outside of each flange. In addition, each beam receives four full strain gage bridges at various radial locations. The beam is then mounted in the vacuum chamber hub, which simulates a cantilevered root condition. The piezos are excited at the first natural frequency of the beam, and the beam is allowed to reach steady state. Finally, the excitation is abruptly stopped and the resulting strain gage transient data is collected for analysis. This data collection is accomplished using a National Instruments Data Acquisition Board mounted in a Macintosh Quadra 950 running LabVIEW.

In order to calculate the damping ratio for each beam, several methods were considered. The first attempt was using a logarithmic decrement approach. It was quickly found that this method did not provide a consistent damping prediction, so another approach was necessary. The current method is based on the Moving-Block Analysis presented by Bousman and Winkler [Bous81]. This method shows much more promise, assuming a large enough block length and reasonable sampling rate are chosen. From our preliinary test results, as the viscoelastic thickness is increased, the non-rotating damping ratio increases substantially. The rotating tests will be completed over the spring and summer 1995..

Another recent concern which has been addressed is that of vibration transmission through the vacuum chamber hub. In order to spin the beams at a reasonable rotational speed, the beam of interest must be counter-balanced by something of equal moment in order to avoid a hub imbalance. The first choice for this counter-balance was another identical beam. However, since the frequency of this second beam was very close to the frequency of the beam of interest, excitation of the primary beam induced significant vibration in the counterweight beam as well. This phenomenon had a significant effect on the transient signal, as can be seen from the strain gage data for both beams presented in Figure 2. In order to eliminate this problem, a steel counterweight system with a much higher natural frequency was developed and installed in place of the second beam. It can be seen from the new transient signal shown in Figure 3 that this new system has eliminated the phenomenon in question. A paper describing these results will be presented at the 1995 AIAA Structures, Structural Dynamics, and Materials Conference [Smith95a].

Future Work

Projected work for the near future includes completion of all of the I-beam testing, as well as fabrication of a set of flat beams to study more closely the effects of viscoelastic location with respect to the beam's neutral axis. In addition, the simple geometry of these new beams will provide a good data set for validation of future modeling efforts. Finally, an attempt will be made at modifying Classical Laminated Plate Theory to allow for a complex shear modulus. The laminate properties provided by this modification may allow the calculation of theoretical damping numbers based on an Euler-Bernoulli approach.

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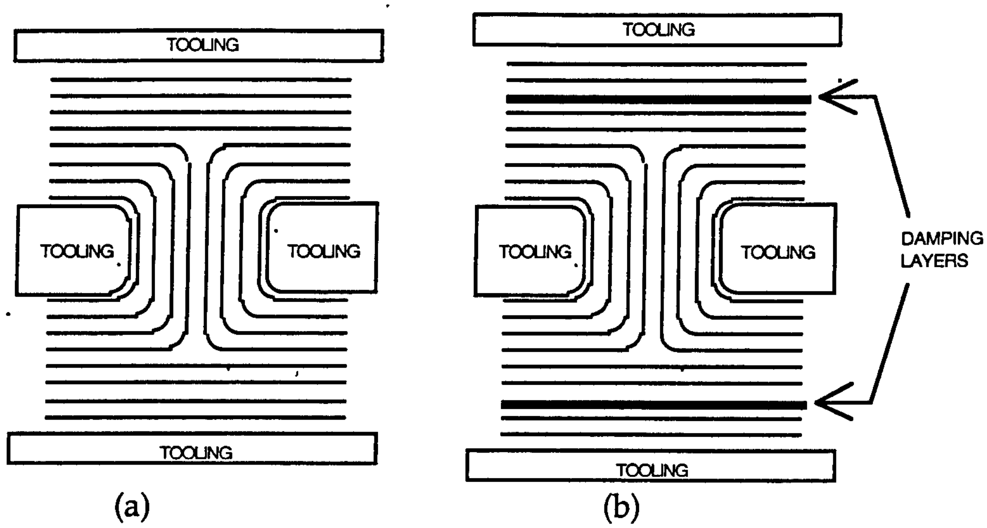


Figure 1. I-beam Layup Configurations

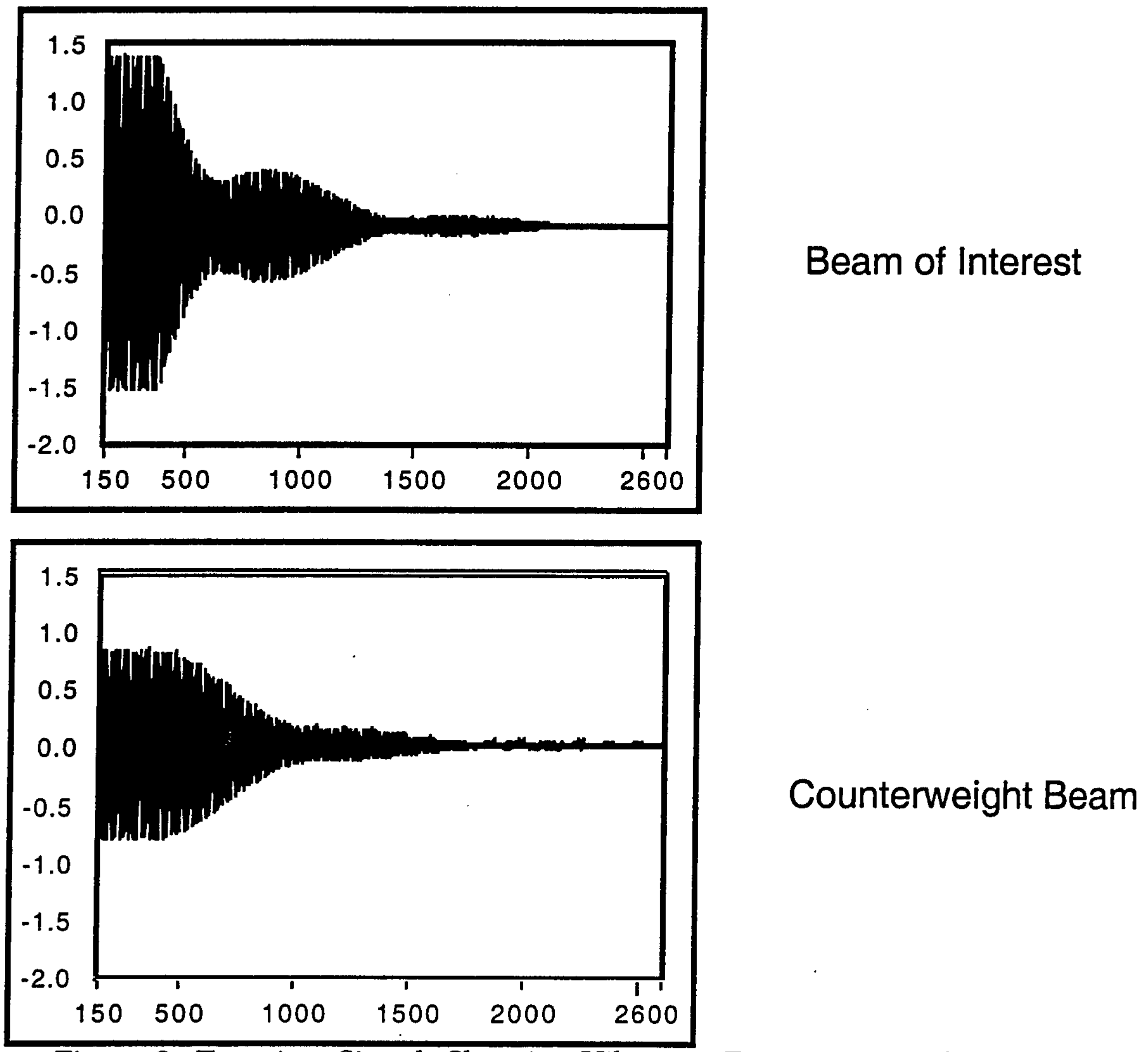
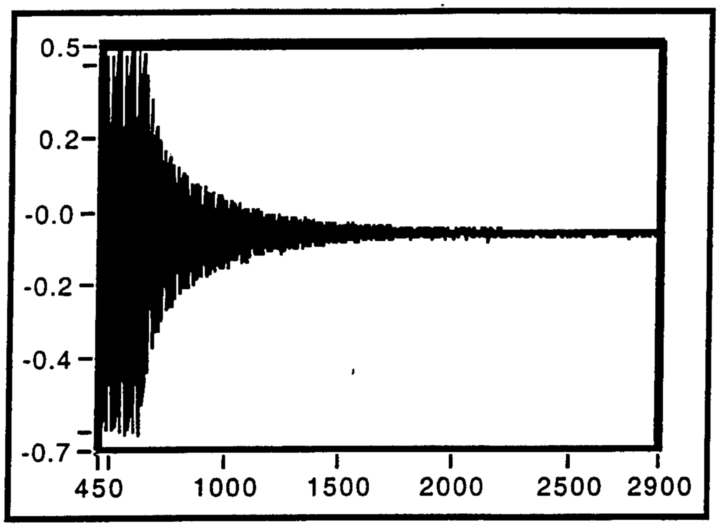


Figure 2. Transient Signals Showing Vibration Transmission Phenomenon



Beam of Interest

Figure 3. Transient Signal for Beam with Steel Counterweight System

Wave Model for Active/Passive Constrained Layer Damping

Subhobroto Nath and Norman M. Wereley

Introduction

In this project, a simple beam model, reminiscent of the Euler-Bernoulli elastic beam model, is being developed to describe active and passive constrained layer damping. The emphasis is on describing the propagation of waves in the structure in order to account for high frequency behavior.

Passive Constrained Layer Damping.

Passive damping will entail increasing the inherent damping of the flexbeam through application of **passive constrained layer damping.** Constrained layer damping involves sandwiching a viscoelastic material between two plates. The bending motion of the plate causes transverse shear in the viscoelastic layer, and hence an energy dissipation, or damping, mechanism is created. Viscoelastic sheet materials are readily available in varying grades of complex shear modulus, so that the level of damping can be tailored to frequency and temperature ranges of typical operation.

Based on preliminary data [Smith95], dramatic increases in damping performance can be obtained by using as little as 30% volume fraction of viscoelastic in a composite or metallic plate. Near critically damped beams were fabricated using the constrained layer damping technique. The viscoelastic materials can either be bonded or co-cured with elastic layers. Examples of such materials are 3M Scotchdamp™ or Soundcoat

Dyad™ materials. The Soundcoat materials are typically surface bonded with an elastic constraining layer completing the sandwich. However, the 3M materials can be co-cured with a graphite-epoxy (350° cure) or Kevlar-epoxy (250°cure) material.

The wave models developed in [Nath95] will be extended to elastic and elastic-viscoelastic-elastic panels, and will be coupled with a model of the acoustic cavity. The wave model for a elastic-viscoelastic-elastic beam is based on a PDE with 6 spatial and 2 temporal degrees of freedom, as below:

$$\frac{mg}{D_t}\frac{\partial^2 w}{\partial t^2} = \frac{\partial^6 w}{\partial x^6} - g(Y+1)\frac{\partial^4 w}{\partial x^4} + \frac{m}{D_t}\frac{\partial^4 w}{\partial x^2 \partial t^2}$$

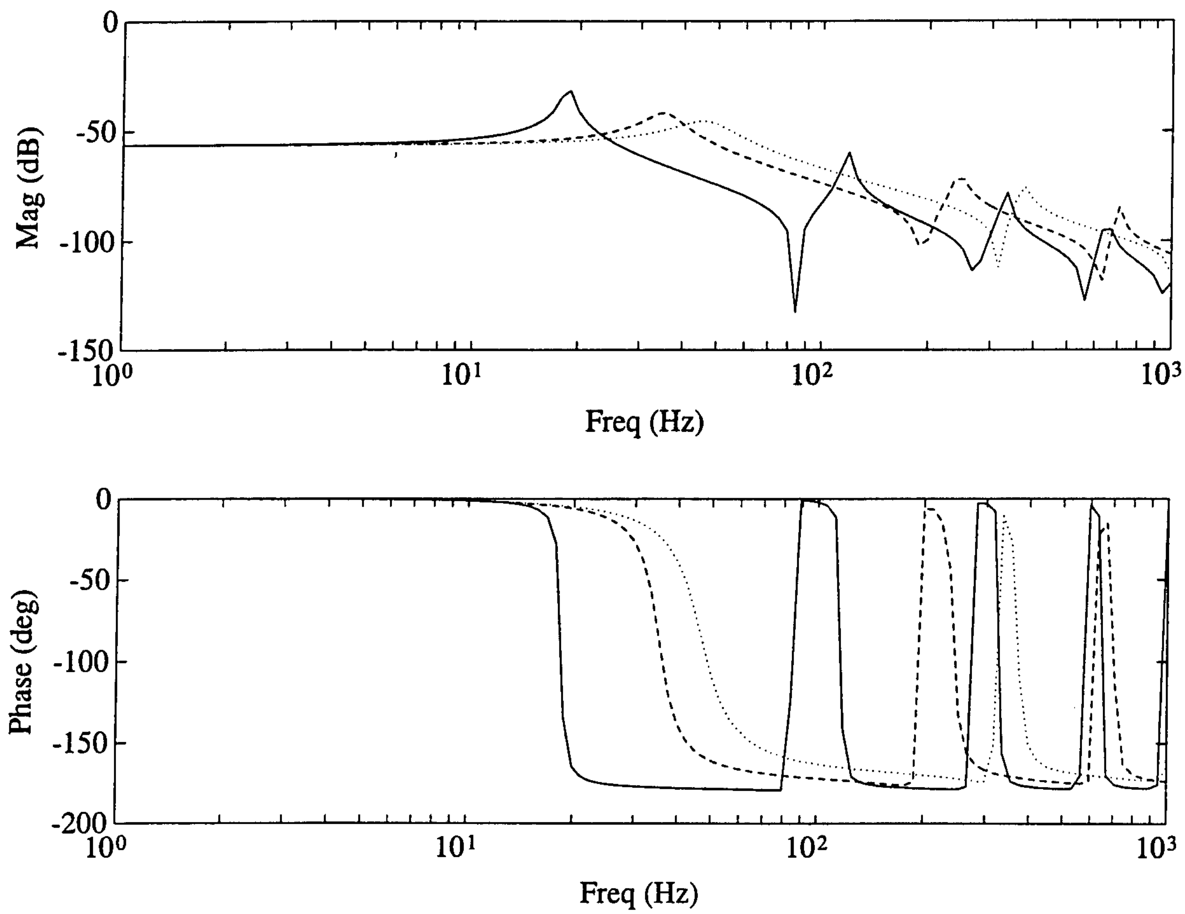
where g, D_t, m, and Y are derived mechanical properties of the beam related to the flexural stiffness and complex shear modulus of the viscoelastic material. A wave model is then developed by satisfying all boundary conditions and compatibility relationships in the beam. Figure 1 illustrates how a cantilevered beam, that has a passive constrained layer damping treatment over its entire length, increases its damping as the thickness of the viscoelastic layer is increased. This is a calculation from the perspective of the transfer function from tip force to tip acceleration, which can then be used in controller design. These beam models are currently being validated experimentally.

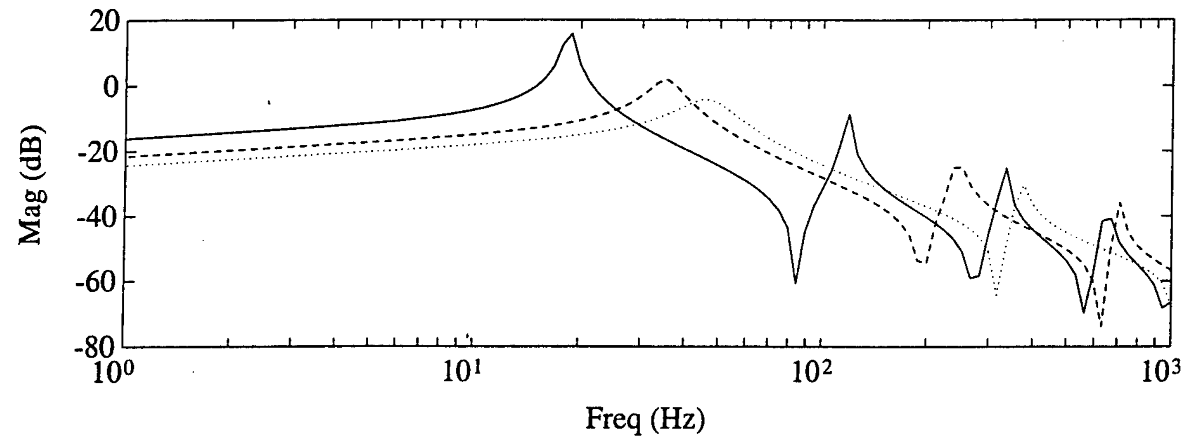
Active Control on a Constrained Layer Damped Structure

A promising active damping strategy is active constrained layer damping (ACLD) [Baz93a]. This technique essentially replaces the constraining elastic layer with an active elastic layer, such as a piezo-crystal (PZT) or piezofilm (PVDF). Thus, the visco-elastic layer can be actively sheared to actively dissipate energy. Pioneering work by Baz *et al* [Baz93a,Baz93b,Baz94] encompasses ACLD treatment of non-rotating and rotating beams. These results are a motivating factor behind the application of ACLD to acoustic applications to augment mechanical plate stability, making the controller more robust. Numerous aspects of ACLD have been examined in the literature, including: partial treatment [Baz93a], full treatment [Baz93a], uniform and shaped piezofilm sensors [Mill87,Baz94], and piezofilm actuators [Baz94]. Feedback control techniques typically used are simple linear methods of proportional or proportional-derivative control laws [Mill87].

The active constrained layer damping model that we have developed is straightforward. Rather than extending existing efforts in FEM modeling on passive and active constrained layer damping, an approach well suited for frequency domain feedback controller synthesis sought. Frequency domain steady state transfer functions are then computed from the input voltage to the active piezo-actuator to beam states, as well as from disturbances to the beam states, using a wave modeling approach. The beam models developed thus far use the complex modulus method to represent the viscoelastic layer, which is data typically supplied by the manufacturer. This work is readily extended to plates in the Euler-Bernoulli Theory context, since a plate is simply a two dimensional beam, and will have direct application to the work proposed here.

Wave modeling is applied to the PDE from [Mead69]. Boundary conditions are developed in [Nath95] that account for the free strain of the piezo-actuator. and allows a calculation of the frequency domain transfer function from the input voltage of the piezoactuator to beam states, such as tip displacement, as shown in Figure 2.

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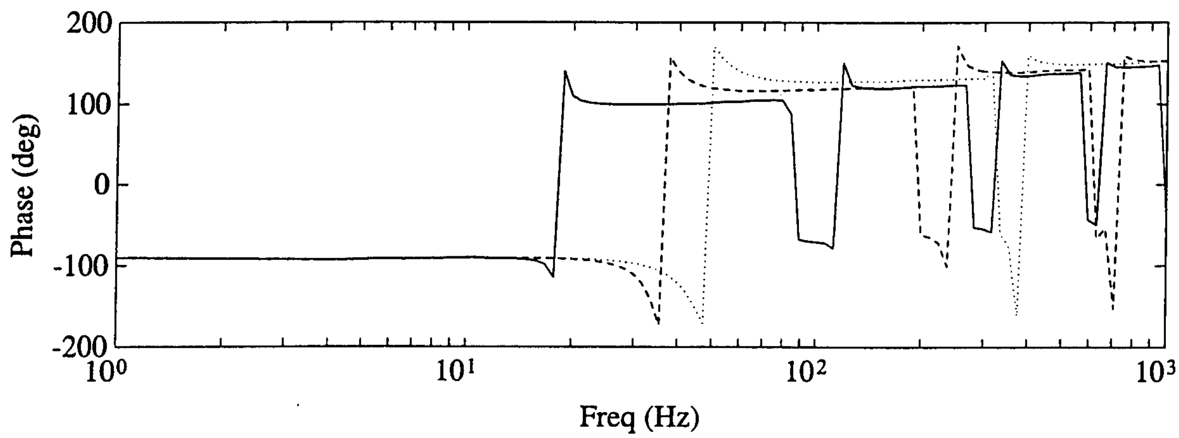
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Phase (deg)
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Freq (Hz)

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Hybrid Active/Passive Constrained Layer Damping for Robust Multivariable Acoustic Control

Sudha Veeramani and Norman M. Wereley

Introduction

A key issue in the development of acoustic control via control of a trim panel is the nature of the model used in the control problem. Typical noise control applications are designed to reduce noise in the audible range of 20 Hz to 20 kHz. A typical stressed skin panel of dimension 24" by 26" by 1/32" thickness might have a first plate bending modal frequency of around 50 Hz. The fourth or fifth mode might lie in the range of 300 to 400 Hz. Typically modal models use only the first few modes in designing the control systems. After the first few modal frequencies, the modal spectral density increases dramatically, and the importance of localized non-uniformity in the trim panel (such as thickness variations) and other variations from nominal structural properties increases, so that modeling uncertainty also increases. Compounding this problem is the relatively abrupt 180° phase shifts that occur at each modal frequency. To improve closed-loop control system performance, knowledge of the frequencies at which these phase shifts occur is critical. Wave models avoid this problem to a certain extent in that modal expansions are avoided, but the fundamental problem still remains - the fidelity of the structural model at high frequency is not as high as desired. When a feedforward or feedback controller is implemented on a structure for which such a model was used in the controller design, the effects manifested in the closed-loop system can include closed-loop instabilities, or much poorer performance than the designed performance or an increase in noise levels rather than the desired decrease in noise levels. Therefore, the control design should account for **stability robustness** and **performance robustness** requirements, that is, the controller should be designed in such a way that the system has guaranteed stability and performance characteristics once the controller is in operation.

Thus, a key ingredient in improving performance in the control of interior acoustics and structure borne noise is to increase the robustness of the closed-loop control system to model uncertainty. An excellent way of improving the robustness of the acoustic controller is to add damping, using either a passive or active strategy. In this application, constrained layer damping is a promising approach.

Damping by a constrained layer can be attributed to the shear motion of the damping layer, along with the associated dissipation [Nashif85,Baz94]. The shear motion is developed by sandwiching a viscoelastic material (neoprene, 3M and Soundcoat products, etc.) or active fluid (such as magneto-rheological fluid), between a structural element and a constraining layer such as a metallic foil. However, the amount of damping can be modified through an active constraining layer, that is, a piezo-electric crystal, so that the magnitude of the shear transmission through the damping layer can be controlled based on feedback of flexbeam data measured using mounted piezoelectric sensors. In this research, we will explore the potential of hybrid active /

passive constrained layer damping in trim panels, using piezocrystals, and metallic or composite structures.

Research Objectives:

The objective of this research is to develop an active / passive hybrid approach to the control of interior acoustics and structurally radiated sound using a smart trim panel fabricated from metallic or composite material. Several approaches will be taken to improving stability robustness and performance robustness, thereby improving overall noise cancellation performance. The passive damping of the trim panel will be increased using an elastic-viscoelastic-elastic sandwich structure, or a passive constrained layer damping implementation. Improved high fidelity structural trim panel models will be developed that account for organic matrix composite materials (such as graphite or kevlar/epoxy materials), various boundary conditions, shear lag damping, compressional damping, and deviations from the ideal Euler-Bernoulli beam/plate theory. The active control of the panel for acoustic noise reduction will be accomplished using piezoactuators, either surface bonded or embedded in the elastic layers of the sandwich structure. Multivariable feedforward and feedback techniques will be developed to maximize noise cancellation performance. In addition, these controllers will be designed to have guaranteed stability and performance characteristics once the controller has been implemented. Smart trim panels will be manufactured in the Composites Research Laboratory using the Accudyne vacuum hot press. These trim panels will be instrumented and experiments will be conducted to validate models, and to verify predicted acoustic cancellation performance.

Progress and Future Work

This project has been partially funded by the Minta Martin Fund for Aeronautical Research at the University of Maryland, and is a new project. Composite trim panels have been fabricated. Two experiments are currently being executed. The first experiment is a structural characterization of the trim panel based on acoustic excitation. Transfer functions have been identified and state space realizations are being developed for purposes of multivariable feedback controller design. These controllers will be implemented using a dSpace digital control system and experimentally evaluated.

Rotor Acoustic Signature Reduction: Computational Fluid Dynamics

James Baeder

Aims

Army aviation goals are to reduce rotor acoustic signature by 6 to 12 dB. Extreme operating conditions generate the most impulsive sources of noise such as that due to blade vortex interactions. Current methods are limited in modeling BVI noise due to the neglect of nonlinear transonic aerodynamics and nonlinear acoustic propagation. Advanced passive designs, such as higher harmonic control (HHC) and advanced planforms and airfoil shapes, are limited by design compromises. Furthermore, detailed wake information is needed to make them successful. Unfortunately, often noise reduction benefits in certain regimes are offset by increased vibrations in other regimes. This task looks at incorporating smart structures effects into Computational Fluid Dynamics (CFD) and Computational AeroAcoustics (CAA) analysis in order to determine the feasibility of using smart structures to dynamically twist the blade for reducing blade-vortex interaction noise.

Approach

Computational fluid dynamics is being used to model the nonlinear, compressible unsteady aerodynamics of an isolated vortex interacting with an arbitrarily pitching airfoil. First, a baseline case is computed, where the airfoil undergoes no pitching motion. Second, based on the computed lift time history simple linear aerodynamic theory predicts what airfoil pitching motion should cancel the vortex interaction generated lift. This pitching motion is then fed into the CFD code. The cycle is then repeated, with the most recently calculated lift as input to calculate an improved predicted pitching motion.

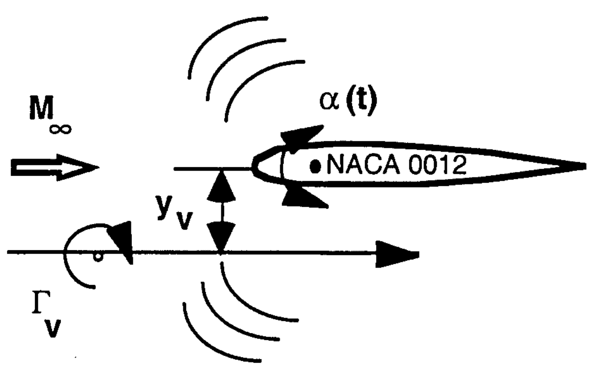

Figure 1 Schematic of an isolated vortex interacting with an arbitrarily prescribed pitching airfoil.

Results

The Transonic Unsteady Rotor Navier-Stokes (TURNS) code has been modified to include the perturbation method for treating flows with known vortices, as well as include arbitrary pitching motion of the airfoil. Two base cases have been examined with freestream Mach numbers of 0.5 and 0.8. For both cases quasi-static airfoil theory has been used to predict the pitching motion.

For the lower Mach number case, the method looks very promising. The maximum pitching angle needed to reduce the fluctuating lift is on the order of one-and-a-half degrees. The first application of feedback reduces the fluctuating lift by more than a factor of two. The second application further reduces the fluctuation to less than one-fifth of the original. More importantly, the time derivative of the lift, proportional to the noise in the far-field, is also reduced. After two applications the peak pressure would be one-tenth of that without any airfoil pitching. Unfortunately the pitching moment is increased to a level approximately five times of that with no pitching motion. Results for the transonic case are less impressive, with almost a reduction by a factor of two in the predicted peak pressure of the acoustics after two applications of feedback. However, the pitching moment is not adversely affected, due to the reduction in shock motion.

Future Work

Current work is investigating the feasibility of implementing such a pitching scheme by determining the limitations of current actuator technology. Preliminary results indicate that the bandwidth is acceptable but the amplitudes available are approximately one-tenth of that needed. Nonetheless, current technology has the potential to reduce the blade-vortex interaction noise by 3dB.

The indicial approach will be investigated to improve feedback over that from quasi-steady theory. Furthermore, sensor requirements will be investigated to see if leading edge pressure differential gauges can be used to sense the impending interaction. If warranted the work will be extended to a three-dimensional rotor blade with possibly a time-varying twist and/or camber distribution.

Relevant Publications

Baeder, J.D., "The Role and Status of Euler Solvers in Impulsive Rotor Noise Computations", To appear in Proceedings of the AGARD Symposium on Aerodynamics and Aeroacoustics of Rotorcraft, Berlin, Germany, Oct. 1994.

Parameswaran, V., and Baeder, J.D., "The Application of Arbitrary Pitching Motion to Blade-Vortex Interaction Noise Reduction", To be presented at AIAA 13th Applied Aerodynamics, San Diego, CA, June 1995.

Amerigo, M.P., and Baeder, J.D., "Feasibility of Arbitrary Pitching Motion Controlled by Piezoceramic Actuators to Reduce Blade-Vortex Interaction Noise", To be presented at AHS 51st Annual Forum, Fort Worth, TX, May 1995.

Rotor Acoustic Signature Reduction: Unsteady Aerodynamics of a Flapped Airfoil

J. Gordon Leishman

The overall objective of this sub-task is to support research into understanding of the usefulness of "smart structures" in rotor airloads and acoustics. This research task is being pursued by first examining the use of trailing-edge flaps. There have been several practical applications of a trailing-edge flap for gust alleviation or to help suppress flutter on fixed-wing aircraft. For helicopter rotors the use of trailing--edge flaps on the blades has, so far at least, found use only for collective and 1/rev. cyclic pitch control. With the advent of smart materials/structures and high bandwidth active control technologies, it is now becoming increasingly feasible to use trailing--edge mounted flaps on rotor blades as a means of higher harmonic cyclic or individual blade control. Coupled with real-time adaptive feedback strategies, actively controlling the blade lift distribution offers tremendous possibilities for reducing blade loads and noise due to wake vortex encounters.

Theoretical studies of these problems using advanced rotor codes such as UMARC require the use of a suitably formulated time-domain aerodynamic theory for the flap. An unsteady aerodynamic theory is required for the problem, firstly because the flap actuation frequency can be several times the rotor rotational frequency, and secondly, because high resolution predictions of rotor acoustics need be made. In addition, since the local effective reduced frequencies based on flap motion often exceed unity, incompressible assumptions are no longer adequate and compressible flow must be intrinsically assumed. Therefore, the objective of the work was to develop an unsteady aerodynamic theory for the effects of the flap that is applicable for subsonic compressible flow.

The approach has been based on indicial function concepts, and is formulated in a computational form suitable for many types of rotor loads and aeroelasticity applications. Results for the airfoil case were used in conjunction with the reverse flow theorems to formulate a solution for the flap. Results show the significance of compressibility effects on the unsteady aerodynamics associated with time-varying trailing-edge flap displacements in a simulated rotor environment. The work on the basic formulation is now essentially complete, and two papers have been published:

Ongoing work is direct toward the acoustic signature reduction concept. Since the unsteady aerodynamic model is written in state-space form, the aerodynamic system matrix can be inverted to find the relationship between a desired output and the required input. The desired output is related to the time rate of change of lift (and hence the pressure field and acoustics) and the required input is the flap schedule. Basically, the equations can be used to find the flap displacement schedule required to attenuate the noise propagated due to blade vortex interaction. Currently, it has been found that for a typical BVI encounter, the amplitude and flap rates required to completely eliminate the noise generated are too large to be practical with current actuators. In addition, the flap displacement produces section pitching moments that may be difficult to tolerate on a rotor system. Ongoing work is directed toward developing a simple threshold limiting controller in order to determine the degree to which BVI noise reduction will be feasible without compromising other aspects of the aerodynamic characteristics.

Publications

J. Gordon Leishman (1994). "Unsteady Lift of a Flapped Airfoil by Indicial Concepts," *Journal of Aircraft*, March-April, 1994.

Naga Hariharan and J. Gordon Leishman (1995). "Unsteady Aerodynamics of a Flapped Airfoil in Subsonic Flow by Indicial Concepts," *36th AIAA Structures, Structural Dynamics and Materials Conference*, 10-12 April, New Orleans, LA.

Novel Hybrid Actuators

Manfred Wuttig

The mechanical properties of Ni50Ti50 deposited on Si and 3C- SiC substrates were studied focusing on the interaction of the film and substrate. This interaction determines the transformation characteristics through interface accommodation and mechanical constraints exerted by the substrate stiffness. Substrate stiffness, controlled by the film/substrate thickness ratio, was found to have a substantial influence on the output energy of the film/substrate composite. A switch type composite based on this knowledge was fabricated and tested.

The thermo-mechanical properties of Terfenol-D thin films deposited on Si substrates were studied by static and dynamic measurements of film/substrate composite cantilevers. The Curie transition, E effect and mechanical damping of the film were measured simultaneously. The stress in the film was controlled by annealing below the recrystallization temperature and determined to vary from -500 MPa, compression, in as deposited films to +480 MPa, tension, in annealed films. The Curie temperature shifts from 80°C to 140°C as the tension increases while the structure of the film remains amorphous. The stress change induced by annealing also drastically effects the film's damping characteristics. The E effect of the amorphous material, about 20%, was used to estimate the magnetostriction.

Publications

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C.M. Su, A. Fekade, M. Spencer and Manfred Wuttig, Stresses in CVD Grown Epitaxial 3C-SiC Membranes, to be published in J. Appl. Phys., Feb. 1995

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Q. Su, T. Kim and M. Wuttig, Switching Effect of NiTi Shape Memory Alloy Films, MRS Symposium Proceedings, 1994 Fall Meeting, to be published

M. Wuttig, H. Zheng and Q. Su, Thermo-Magneto-Mechanical Properties of Thin Film Terfenol-D, MRS Symposium Proceedings, 1994 Fall Meeting, to be published

Quanmin Su, Cecile Bailly, Manfred Wuttig, Sean Corcoran and Karl Sieradski, Streess Evolution Kinetics in Ultrathin Sputtered Au Films, MRS Symposium Proceedings, 1994 Fall Meeting, to be published

Quanmin Su, D. X. Huang and, Manfred Wuttig, In-Process Evaluation of Kinetic Energy of Sputter Depositing Atoms Using Multijunction Thermal Converters, MRS Symposium Proceedings, 1994 Fall Meeting, to be published

Quanmin Su, T. Kim, Y. Zheng and Manfred Wuttig, Thermomechanical Properties of NiTi and Terfenol-D Thin Films, International Conference on Shape Memory Materials, Beijing, Sept. 25 to 28, 1994

Quanmin Su, Y. Zheng, A. Roytburd and Manfred Wuttig, Substrate Stress Controlled Magnetic Domains in Amorphous Terfenol-D Films, J. Appl. Phys. Letters, to be published

Magnetostrictive Actuators

M. (Appa) Anjanappa

Specific Aims

To investigate and develop embeddable Magnetostrictive actuators to actively suppress vibrations in rotorcraft blades.

Results

The overall objective is to embed magnetostrictive particles in the spar of the smart rotor and actuate them with embedded coils for vibration suppression. The first phase of this work was focussed on theoretical and experimental study of Magnetostrictive Mini Actuators (MMA). The knowledge gained during this phase has become the stepping stone to design, model and control the embedded magnetostrictive particle actuators. The progress of the project in this reporting period is behind schedule in the area of experimental work which we hope to catch up in the next six months. However, the theoretical work is on-schedule. One contributing factor for the delay in experimental work is that I, Appa Anjanappa, was on six month sabbatical leave during this period. Following are the specific tasks that have been completed in this reporting period.

Work towards validating vibration suppression capability of homogeneous cantilever beam with surface bonded Magnetostrictive Mini Actuator (MMA) is under progress. The results will be published soon.

An improved mathematical model of an ALPLEX cantilever beam embedded with Magnetostrictive particle actuators is being completed. This model will be able to incorporate the effects of longitudinal static stress and longitudinal vibration on lateral vibration of a cantilever beam. In our case, the longitudinal quasi-static stress is present due to thermal effects of resistive coils. The longitudinal vibration is primarily due to either unsymmetric actuation of two actuators or due to dc offset or due to actuation of one actuator only. In practical applications it is certain that these two non-idealistic situations do exist. Hence, these unwanted side effects must be quantified and if possible use them to our advantage in suppressing the lateral vibration. Preliminary simulation results indicate that with proper design they can be made to work in our favor.

Figure 1 shows the proposed experimental setup to validate this model. The experimental facility has been completed. Sample ALPLEX beams are under fabrication. The exciting filaments, as shown in the figure, indicates that only three out of n-filaments will be chosen at any given time. The selection of the three optimum filaments will be based on the work in progress by Dr. Tasker.

Work towards extending the above work to composite beams, required for rotorcraft blade application, will be performed in the future.

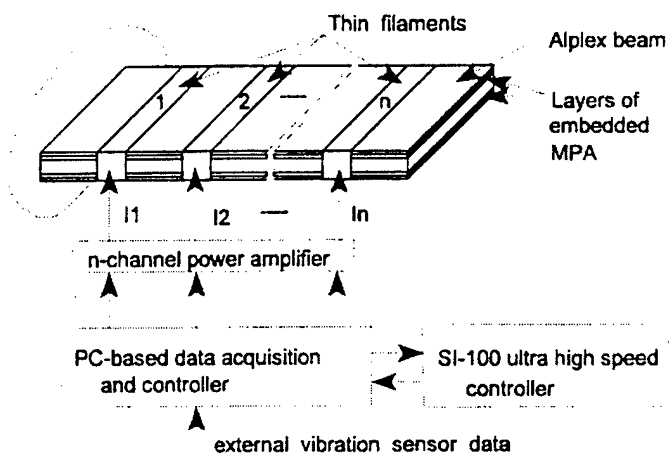

Figure 1. Proposed Experimental Set Up to Validate the Model on Alplex beam embedded with Magnetostrictive Particle Actuators (MPA)

Publications

J. Bi, and M. Anjanappa, (1994). "Investigation of Active Vibration Damping Using Magnetostrictive Mini Actuator," SPIE Conf. on Smart Structures and Materials Vol. 2190-82, February, Orlando, Florida, pp. 171-180.

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Bhattacharya, B., Krishnamurty, A.V., Anjanappa, M., and Bhat, M.S., "Dynamic Modelling of Smart Composite Beams," Proceedings of Development in Advanced Composites & Structures, September 17, 1994, pp: 25-30, Hyderabad, India.

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Interior Acoustics Control

Balakumar Balachandran

Research Objective

The overall aim of this task is to help in the development of viable active control schemes for reducing noise in the interior of a rotorcraft; a specific objective is to control band-limited noise transmitted through the trim panel by using piezoelectric materials.

Approach

Throughout the course of this task, which was initiated in September 1993, analytical and experimental efforts have been undertaken to control band-limited noise transmitted through a flexible panel into the interior of a three-dimensional enclosure (shown in Figure 1). (In the past year, the focus has been primarily on experimental efforts aimed at controlling bandlimited disturbances encompassing one or more structural and/or enclosure resonances.) The rigid walls of the enclosure are constructed from acrylic material, and the flexible wall, which is clamped along all four edges, is constructed from aluminum material. Active control of interior noise is realized by using Lead Zirconate Titanate (PZT) piezoelectric actuators bonded symmetrically to the flexible boundary. Polyvinylidene fluoride (PVDF) film patches mounted on the flexible wall are used as vibration sensors, and condenser microphones placed inside and outside the enclosure are used as acoustic sensors. In the analysis, in the previous years, optimization techniques were employed in the frequency domain to determine the optimal voltage inputs into the actuators and the sound pressure levels in the enclosure for three different performance functions. These functions are based on the squared pressure in the enclosure, the sum of acoustic potential energy and panel kinetic energy, and the sum of acoustic potential energy and air particle kinetic energy. In current analytical work, initiated towards the end of the past year, a mechanics based state-space model is being developed to control enclosed sound fields with many dominant tones. In the experiments of the past year, digital feedforward control schemes based on filtered-U gradient descent algorithms were implemented to minimize the sound pressure level in the enclosure and/or the panel vibration levels.

Results

Through the analytical and experimental efforts of the previous years, it was demonstrated that substantial ``local" noise reductions (about 30 dB) could be realized by using piezoceramic actuators on the trim panel in the presence of tonal disturbances below the Schroeder frequency. However, the experimental results obtained this past year for bandlimited disturbances including multiple tones have not all been promising. In Figure 2, representative results obtained in one of the experiments is shown. Noise reductions are discernible at some of the disturbance frequencies. In the successful cases, the overall ``local" noise reductions have been in the range of 2 dB to 20 dB. It is speculated that the success is limited by the following factors: a) actuator and sensor configurations and b) control strategy and algorithm. These two factors have to be well understood prior to full scale implementation in a rotorcraft. Currently, a time-domain analysis based on a state-space model, which is a unique feature of this work, is being undertaken to obtain a better understanding of the controller.

Significance

In helicopter cabins, the major contributors to noise are the gear transmission, the main rotor, and the tail rotor. While the sound energy due to the gear transmission is spread across high frequencies (above 500 Hz), the sound energy due to main and tail rotors is spread across low frequencies (below 500 Hz). To achieve significant noise reduction, one will need to consider attenuation of a sound field with many dominant tones. The limited success achieved in the task thus far is indicative of the strong possibilities for active control of bandlimited disturbances in helicopter cabins employing a combination of vibration and acoustic error sensors.

Interactions

Over the past year, interactions have taken place with Dr. Raman Mehra of Scientific Systems Company (SSC), Inc., Boston, Massachusetts; Ms. Susanna Shank of Bell Helicopter Textron, Fortworth, Texas; Dr. Gopal Mathur of McDonnel Douglas Aircraft Company, Long Beach, California; Dr. Amr Baz of Catholic University of America, Washington, D.C.; Dr. David Elliott of Institute of Systems Research, University of Maryland, College Park, Maryland; and Mr. Donald Sofge of NeuroDyne Inc., Bluemont, Virginia.

In the work being undertaken with Scientific Systems Company, determination of appropriate state-space models from experimental data is being pursued and an implementation of controller based on SSC algorithms is to be carried out. In the work being undertaken with NeuroDyne, some novel adaptive control strategies are to be tried out.

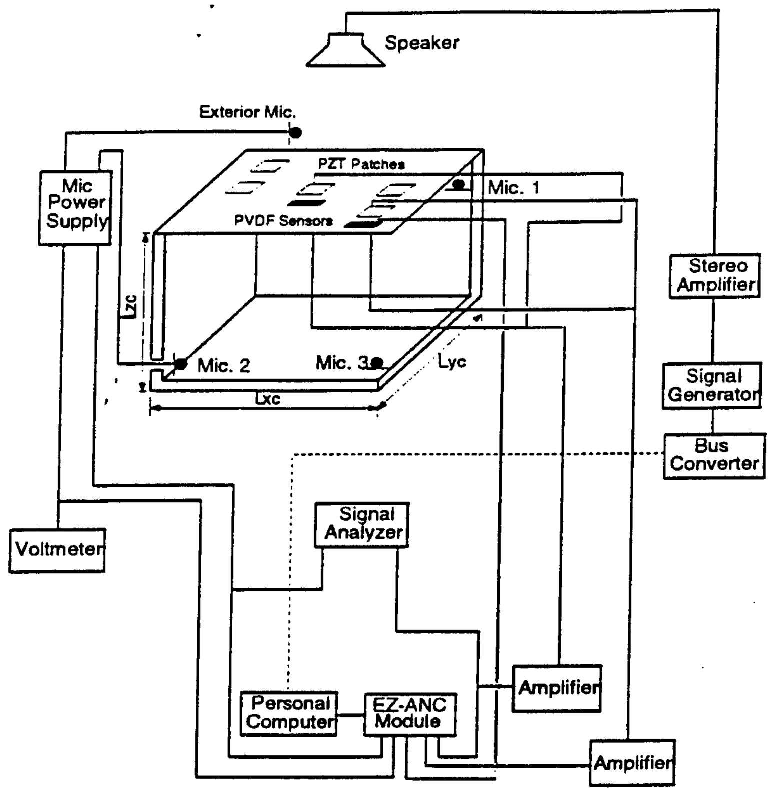
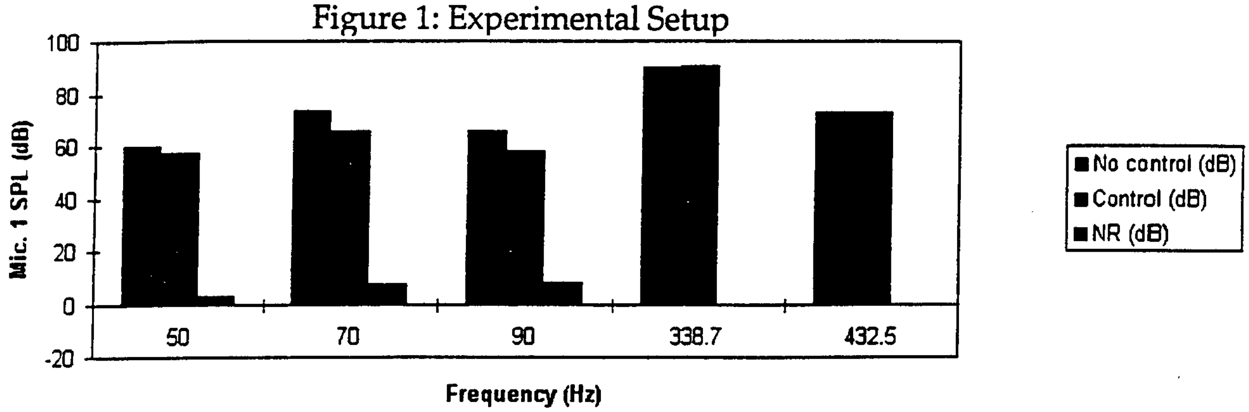


Figure 1: Experimental Setup



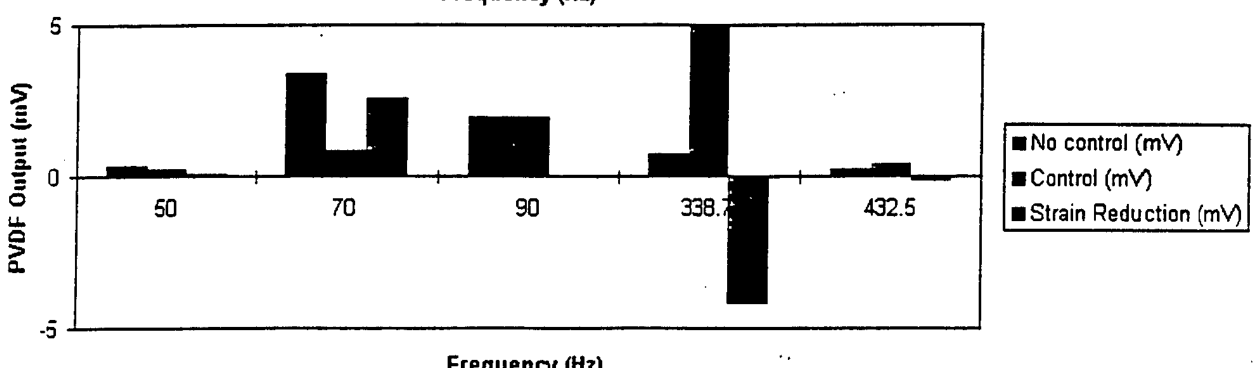


Figure 2: Experimental Responses for multiple actuator tones at (2,1) and (1,2) panel resonances and (0,0,1) and (1,0,1) enclosure resonances using actuator pairs 1 and 2 and Mic. 1 and PVDF 1 error sensors.

Damage Detection in Rotorcraft Blades Using Element by Element FEM Sensitivity Analysis

Jason Kiddy and Darryll Pines

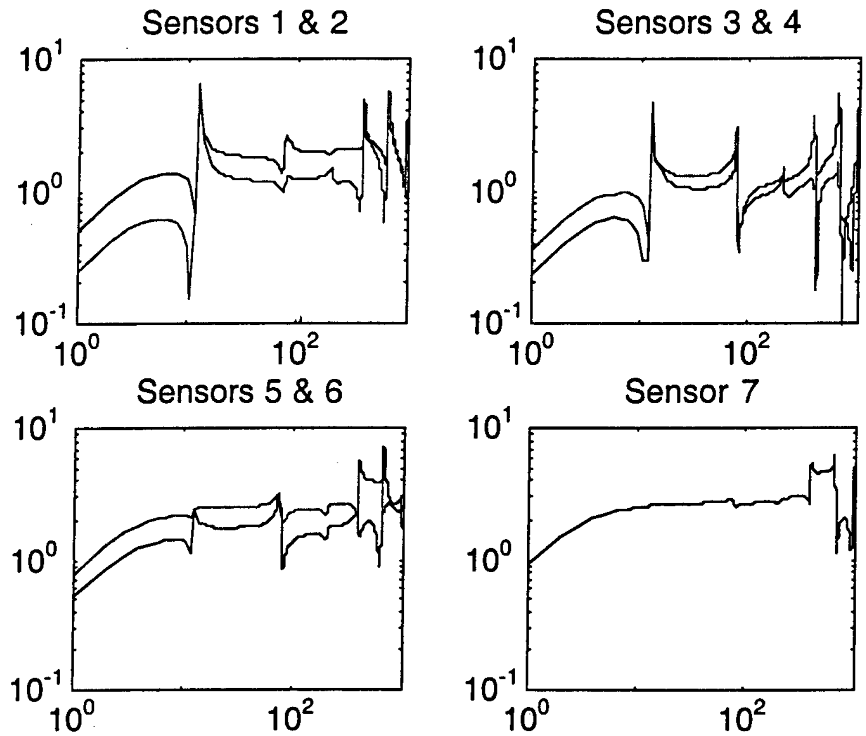
The objective of this research is to develop and experimentally validate a modal based damaged detection algorithm for a composite rotor blade. This damage detection approach is aimed at detecting damage which affects the global properties of the blade. The ultimate goal is to develop a real-time health monitoring scheme for main rotor blades. The first stage of the damage detection methodology is the development of an accurate finite element model (FEM) of the rotor blade. From the derivation of the FEM model, the sensitivities of the elemental mass and stiffness matrices can be calculated with respect to changes in structural parameters. For the purpose of damage detection, these structural parameters are the mass and stiffness of each element. These sensitivities and the finite element model are then used along with the measured eigenvalues and eigenvectors from the rotor to detect and characterize damage.

Work on this research effort began in May of this year. For simplicity, initial efforts are focused on developing and validating the above approach for a rotating beam in vacuum. This simplifies the algorithm by eliminating aerodynamic forcing on the rotating blade. However, the large centrifugal forces are still retained. To this end, a detailed finite element model of a rotating beam has been developed and the associated sensitivities have been calculated. The damage detection algorithm was then developed and validated analytically. Work has now proceeded to experimental validation of the approach. Two fully sensored beams were created and are now undergoing benchtop testing.

Analytical results have been excellent. The damage detection algorithm has been shown to successfully detect and characterize of less than 1 percent damage in mass or stiffness of any element. Experimental validation of the methodology is proceeding well. Two carbon graphite-epoxy composite beams have been built. Two piezoelectric actuators have been mounted to the root to provide bending actuation. Furthermore, each beam has been fitted with seven piezoelectric thin-film (PVDF) sensors. These sensors provide a distributed set of strain measurements along the span of the beam. Some initial difficulties have been met with using the PVDF sensors instead of strain gages. However, these problems have been overcome and testing of the undamaged beam has been completed.

After experimental validation of the rotating beam in vacuum has been completed, the next task will be to examine the sensitivities of the hub loads to damage in a rotor blade. Finally, aerodynamic effects will be incorporated into the damage detection algorithm and the methodology will be tested on Froude scaled rotors with embedded sensors.

If this method proves viable, it will be possible to implement a real-time health monitoring system on a main rotor blade system. This technology would enable a helicopter pilot to be aware of the condition of his rotor blades. Educated decisions can then be made which will allow the helicopter to be flown safely. This is of particular importance in the case of small arms fire where ballistic damage to the rotor system



could occur easily.

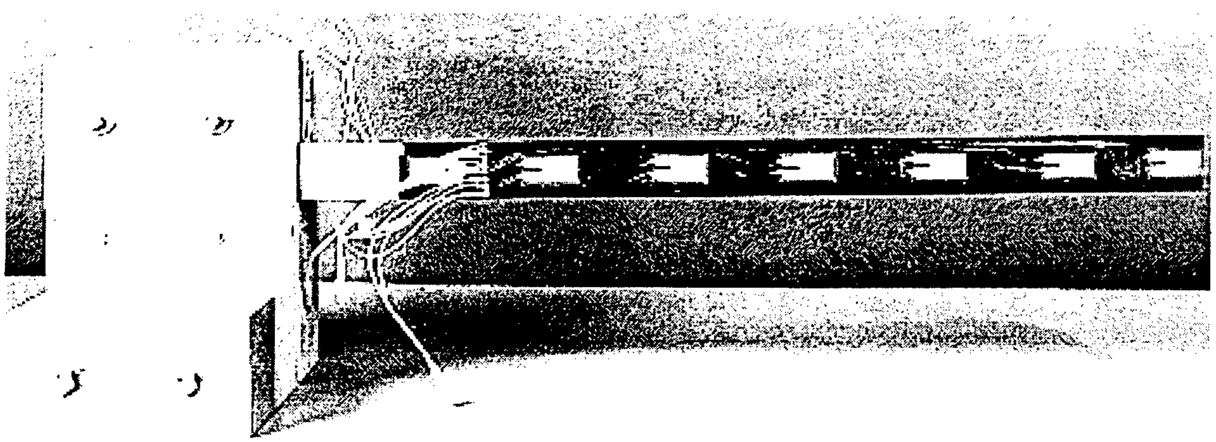


Figure 1. Experimental Beam

Figure 2. Experimental Transfer Functions

Optical Fiber Strain Sensors: Phase Strain Relationship

James S. Sirkis

Technical progress in two subtasks is described.

Prediction of the Fatigue Life of a Laminated Composite using Optical Fiber Sensors

Harmeet Singh and James S. Sirkis

The objective of this task was to develop a system of optical fiber sensors that is capable of monitoring the fatigue damage in composite materials. It has been reported in literature that as the fatigue damage in composite grows, the effective stiffness of the composite degrades. We had suggested that the fatigue life degradation can be measured by using continuum damage mechanics which relates the material degradation in the composite to the host's effective stiffness reduction. However, to accurately predict the diminished fatigue life of the composite host it was important to measure complete state of strain in the composite host. Unfortunately to date there are no sensors available that can measure complete state of strain inside the composite host. Therefore, we suggested a novel configuration of optical fiber sensors that can be very easily embedded in the composite material to measure the complete state of strain. In summary, the aim of the project were (1) to develop a continuum damage mechanics (CDM) based model to relate the stiffness degradation in composite to the remaining fatigue life of the host, (2) develop an optical fiber sensor capable of measuring three states of strain using a single optical fiber sensor, and (3) combine the CDM model with the optical fiber sensor to predict the remaining fatigue life in the composite material. The proposed task is still being pursued with the same objectives in mind and the next paragraph describes the current status of the task.

The first part of the task pertaining to the development of CDM is already finished and the work in progress is concerning the development of three-parameter optical fiber sensors. Two-parameter fiber sensors have already been developed using the novel ILFE sensor, as shown in Figure 1, and a conventional Intrinsic Fabry-Perot sensor. The results obtained from the ILFE sensor is shown in the subsequent figure titled ``dynamic strain measured by the Fiber-Optic ILFE sensor and resistance strain gage" and illustrates the excellent agreement between the conventional resistance strain gage sensor and the ILFE sensors. The current research directed towards the integration of the third parameter sensor to the already developed two-parameter sensor.

Publications

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H. Singh and J. S. Sirkis (1994). "Direct Extraction of Phase Gradients From Fourier Transform and Phase-Step Fringe Patterns," *Applied Optics*, 33(22):5016-5020.

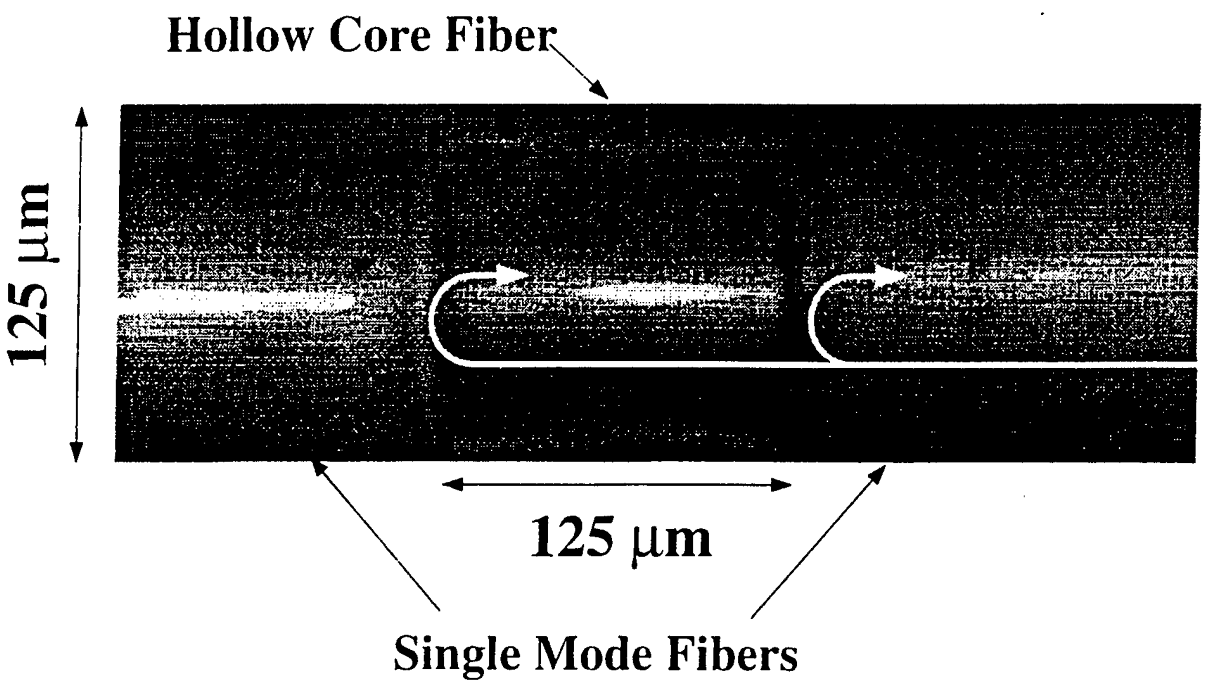

Figure 1. In-Line Fiber Etalon (ILFE) Strain Sensor

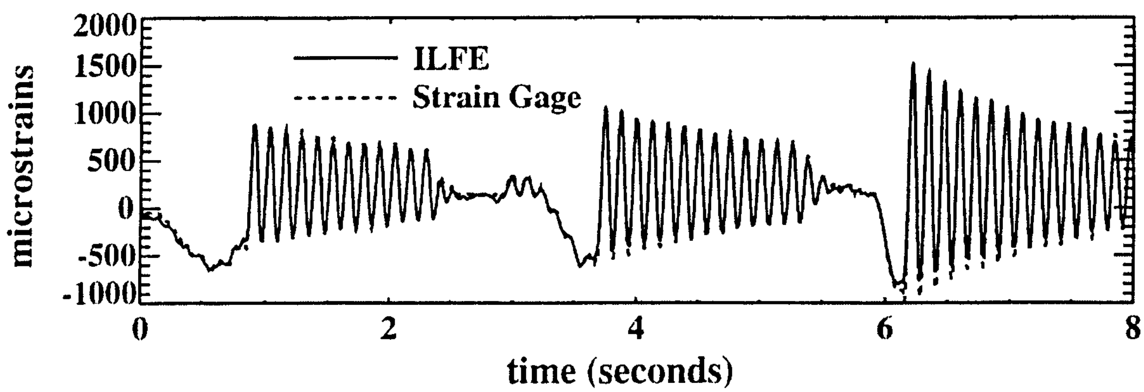

Figure 2: Comparison of Dynamic Strain Measured by the Fiber-Optic ILFE Sensor and Resistance Strain Gage

H. Singh, J. Sirkis, J. Andrews, and R. Pulfrey (1995). "Evaluation of Integrated Optic Modulator-Based Detection Schemes for In-Line Fiber Etalon Sensors," Submitted to the *J. of Lightwave Technology.*

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Location and Magnitude of Impact Detection in Composite Plates Using Neural Networks

Richard T. Jones and James S. Sirkis

Specific Aims

The specific aims of this research effort were outlined in the proposal. These include using a closed-form analysis to understand the structural system that is to be monitored, application of a sensor array to the analytical system, refinement of the analytical model by using the sensor data, development of a neural network paradigm to locate and quantify the evolution of damage in the continuous structure, development of the appropriate input-output relationships for the neural network, training the neural network on analytical and experimental data, and experimental and analytical verification of the damage detection methodology on both isotropic and anisotropic plate structures.

Some of these goals evolved in the course of this research study. Due to dissimilarities between the analytical strain data and experimental strain data, the neural network could not be presented with a mixture of analytical and experimental data. However, separately they provided accuracy of the same order. Experimentally and analytically, the impact location detection methodology has been tested and proven adequate on an isotropic plate. The magnitude of impact methodology has been tested and proven adequate analytically on an isotropic plate. The magnitude of impact detection will not be tested experimentally prior to the contract expiration date (end of summer, 1995), due to time constraints. Furthermore, the analytical and experimental development and verification of a neural network methodology for anisotropic plates will not be performed.

Results

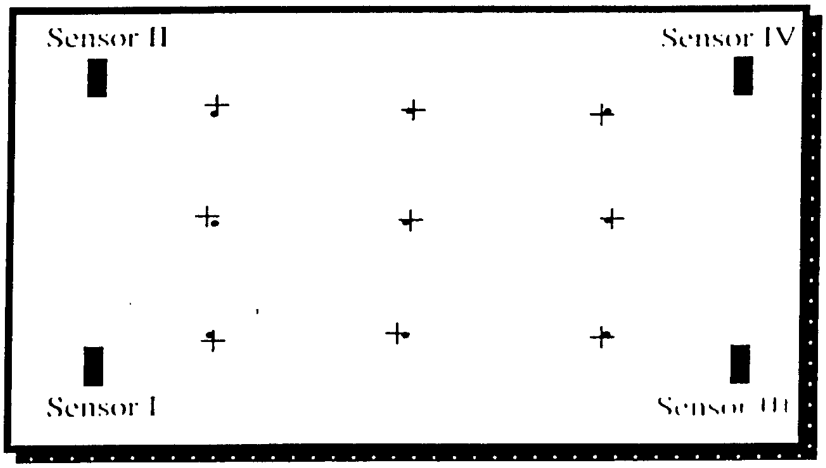
The main goal of this research project is to develop a method of determining the location and magnitude of an impact on composite plates using neural networks. This is important is several areas, including space craft applications, where small debris in low earth orbit can strike the hull of a craft, causing damage. It would be beneficial to know the exact location of the impact and it's magnitude. Thus, a 'smart' plate that could determine these two quantities of interest could provide a meaningful addition to the ever growing list of smart structures.

Specifically, it was found that by using a backpropagation neural network, both the location and magnitude of the impact could be determined. For impact location detection, the neural network uses the integrated real and imaginary parts of the FFT of strain evaluated at each sensor for inputs, and the location of the impact as outputs. For impact magnitude detection, the neural network uses the integrated real and imaginary parts of the FFT of strain evaluated at each sensor for inputs, along with the coordinates of the impact. The sole output of this neural network is the impact magnitude level. These findings are indeed significant for health monitoring of structures. This neural network approach has been trained and tested using both analytical and experimental data from a 2 ft. by 3 ft. fully clamped plate.

The neural network is trained on analytical data using 63 training impacts, and tested using 100 randomly located impacts. It was found that impacts could be located with an RMS error of 0.822 centimeters. The neural network was then trained using 67 experimental training impacts and tested using 71 randomly located impacts. Using experimental data, it was found that impacts could be located to within 1.398 centimeters. Figure 1 shows a subset of the results for neural networks trained on analytical (Fig. 1a) and experimental (Fig. 1b) data. Although the nine impacts shown in each case are symmetric, this is not the case for the entire test set. The test impacts each have random coordinates that differ from those of the training set. The nine symmetric impacts shown are simply given to show the relative scale of the neural networks' accuracy.

Several unexpected problems arose with the experimental data collection. Some of these include DC shifts in the strain traces, problems with strain trace storage, high frequency signal noise, and dominance of certain plate modes in the FFT of strain. These problems were overcome by post processing the data, which can be accomplished with a simple program running on a personal computer.

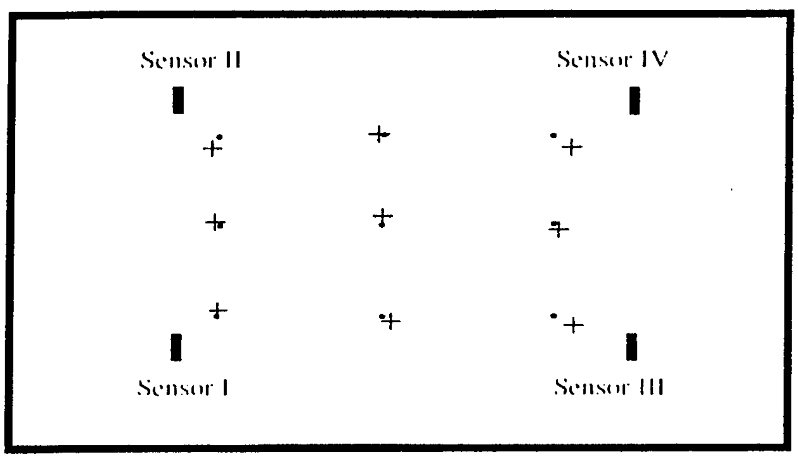
For full-scale application, implementation of this technology would be limited by the cost of obtaining the training set. Otherwise, plate substructures can be easily outfitted with sensors, which can be interrogated with relatively simple electronics. The inputs for the neural network can be created using a simple personal computer. The neural network itself can be recreated on a chip.



. - Actual coordinates of impact.
+ - Neural network solution.
▌ - Sensor placement.

Analytical Results, RMS error = 0.82 cm

(a) Analytical result



▌ - Sensor Locations
. - Actual Impact Location
+ - Neural Network Solution

Experimental Results, RMS error = 1.4 cm

(b) Experimental result

Figure 1: Results for neural networks trained on analytical and experimental data. Although the nine impacts shown in each case are symmetric, this is not the case for the entire test set.

Structural Integrity of Smart Structures : Analysis

Ahbijit Dasgupta

Objectives And Specific Aims

Develop design, simulation and fabrication methods for use of distributed embedded miniactuators, in order to minimize obtrusivity and maximize structural integrity of smart structures. Design tools under development include: (i) closed-form models using Eshelby techniques, (ii) novel finite element schemes for coupled boundary value problems, especially in magnetomechanical smart structures. (i) To combine Eshelby's equivalent inclusion techniques with a generalized Hamilton's principle, for modeling adaptive structures with distributed miniactuators, and to verify results experimentally.

(ii) The primary objective is to develop the capability to reliably model magneto-mechanical interactions in smart structures incorporating magnetostrictive devices (sensors or actuators). For this purpose, a three dimensional magnetostrictive finite element is being developed that may be used with existing commercial and research finite element packages.

(b)Magnetostrictive Terfenol-D is ideally suited to smart structure applications on account of its actuation and sensing capabilities. As applications get more complex, tools for accurate analysis of these smart structures become essential both for design and for performance and integrity evaluation. The magnetostrictive finite element under development will combine all of the above capabilities and will therefore go far beyond our stated objective of reliably modeling the structural integrity of smart structures.

Progress

A variational principle for magneto-mechanical interactions, incorporating all the inherent non-linearities (non-linearities in the magnetic field variables and asymmetry of the Cauchy stresses) has been derived. To start with, a two-dimensional, linearized finite element was developed and its application to modeling the actuation and sensing functions of Terfenol-D were demonstrated last year (see the three conference papers attached). This has since been enhanced to three dimensional capability and can handle field dependent (non-linear) material properties.

New developments

Study of the literature and interaction with other active researchers in this area (Prof. Anjanappa of UMBC, Prof. Allison Flatau of Iowa State University and Drs. Kristl Hathaway, A.E. Clark and co-wokers at NSWC, Silver Spring, MD) during the course of our development of an appropriate form for the constitutive behavior of Terfenol-D for the non-linear code opened up a new basis for formulating the finite element problem, one in which field dependence is described in terms of magnetization instead of magnetic field. This formulation has not only a stronger physical basis but also the big advantage that magnetostrictive as well as magnetic properties may now be characterized uniquely by the state of magnetization and need no longer depend upon the state of stress. These significant advantages and need of the applications industry for a more reliable and consistent characterization methodology motivated a new finite element formulation based upon magnetization. Detailed equations were derived on the above basis and a new magnetization based finite element code is now under development.

(i) Closed Form Methods:

b. Results: Adaptive structure with mini-actuators are more reliable and more integrable with other element in the smart system. However, these mini or micro actuators cause a three-dimensional problem and eigenstrain techniques are best suited for such analysis. So, the main objective of this study is to develop a three dimensional technique to model adaptive structures. The study shows the use of eigenstrain techniques for modeling the interaction between micro-actuators and the surrounding host in active vibration applications.

The dynamic response for adaptive structures with many small mini-devices is well develop for adaptive stiffening and adaptive damping. The obtained results show the capability of eigenstrain techniques to model the mechanical interaction issues and the ability of mini actuators, representing less that 10% of the host volume, to change the dynamic behavior of the adaptive structure.

Experimental setup was build over the past year, 1994, and tested. The adaptive structure is a cantilever beam made of Alplex and it has eight embedded mini devices made of PZT-5. The obtained experimental results show dynamic behavior similar to the analytical results for adaptive stiffening and adaptive damping cases.

The obtained results demonstrate the capability of distributed piezoceramic mini-actuators in active vibration control and give good impression for building a full scale beam with many embedded mini-actuators.

Publications

K.S. Kannan and A.Dasgupta (1994). "A nonlinear finite element scheme for modeling the magneto-elastic response of magnetostrictive structures", SPIE Conf. on Smart Structures and Materials, Orlando, Florida, SPIE Vol. 2190.

K. S. Kannan and A. Dasgupta (1994). "Finite element scheme for modeling the magnetoelastic response of magnetostrictive smart structures", ICIM '94, pp. 719-730, Williamsburg, VA, June .

K. S. Kannan and A. Dasgupta (1994). "Finite element modeling of multi-functional composites with embedded magnetostrictive devices", Proc., ASME Winter Annual Meeting. AD-Vol. 45/MD-Vol. 54, pp. 21-28, Chicago, IL.

A. Dasgupta, A. and A.A. Alghamdi (1994). "Transient response of an adaptive beam with embedded piezoelectric microactuators," SPIE Conf. on Smart Structures and Materials, Orlando, Florida, pp. 153-164, SPIE Vol. 2190.

A.K. Jain, A.A. Alghamdi, A. Dasgupta, and J.S. Sirkis (1994). "Effective properties of 1-3 piezocomposites using eigenstrain method and mori-tanaka scheme," ASME Winter Annual Meeting, AD-Vol.45/MD-Vol.54, pp. 67-73.

A.A. Alghamdi, A. Dasgupta (1994)"Experimental investigation of adaptive beam with embedded devices," 31st Annual Technical Meeting of Society of Engineering Science, Texas A&M University, College Station, Texas, October 10-12, 1994, in press.

Model Identification Schemes

Frederick A. Tasker

Specific Aims

The specific aim of this task is to develop methods for identifying smart rotor characteristics for use in vibration control and damage detection.

Progress Report

Several concepts for a smart rotor involve the integration of induced strain actuators, sensors and associated electronics distributed across each blade. Since these elements become part of the structure, there is a significant possibility of altering the distribution of structural properties such as mass, stiffness, damping and various offsets of the system. If one considers the complexity of the dynamics of full scale rotors it is apparent that accurate knowledge of the distribution of structural properties is essential, especially in light of the distributed nature of the induced strain actuators. There is therefore a need to develop experimental techniques for obtaining such information and such methods should ideally include information available from analytical models.

A potentially more significant reason for estimating the distribution of structural properties in a smart rotor is the detection and location of structural damage. Structural damage is reflected as localized changes in the spatial distribution of structural parameters which may then be estimated from distributed response information.

Distributed parameter estimation schemes, often referred to as Model Refinement or System Identification, are under investigation for other smart structure applications, but these are heavily dependent on linear dynamics and are therefore of limited use for helicopter rotors. Due to the complex nature of the forward problem of solving for the rotor response, the inverse problem of estimating the distribution of rotor structural parameters from experiments has received little attention . This capability is however quite important for the reasons discussed above.

(i) Distributed Parameter Estimation Scheme

We have developed a new scheme for identifying distributed rotor structural dynamic parameters from nonlinear rotor response in vacuum. This identification approach uses the structure of the dynamic equations obtained from analytical modeling and approximate information about the parameters. Several methods, such as spatial and temporal Finite Elements and modal reduction, used in rotor dynamic analysis for solving the forward problem are included in the scheme. These are then combined with techniques that are pertinent only to the inverse problem. As an example, modal responses are obtained from multiple sensors on a blade through Kinematic Modal Filtering which enables a rapid reduction of a large number of measurements.

Kinematic Modal Filtering as well as estimation of distributed parameters are made feasible by the smart structure sensing philosophy.

The identification method has been developed using numerical simulations of a nonlinear flap-lag model in vacuum. This model which includes quadratically nonlinear Coriolis terms departs from linear models assumed in other model refinement schemes. The method is successful in estimating distributed mass properties and lumped modal damping for a two-element Finite Element formulation having linear distribution of mass, $m(x) = \alpha_1 + \alpha_2 x$ over first element and $m(x) = \alpha_3 + \alpha_4 x$ over the second element. The results also include estimation of a diagonal modal damping matrix.

The results show that the distributed mass and modal damping values are well identified from the modal representation. A significant finding was that the identifiability of the mass parameters $\{\alpha_i, i=1,..,4\}$ was found to improve substantially with the presence of the nonlinear Coriolis terms.

(ii) Sensor Placement for Kinematic Filtering.

An important issue in the experimental implementation of the above method is the success of the Kinematic Modal Filtering scheme for obtaining modal responses from distributed response measurements on the blade. Modal Filtering is also used in Modal Vibration Control and Load Estimation. The success of this filtering scheme depends mainly on the number and particularly the placement of sensors. Under this task we have developed methods for sensor placement to maximize the quality of the observed modal response. A general framework was developed for sensor placement which permitted the specification of different criteria based on the variances of the response. In particular it was possible to include the effect of non-primary modes in the sensor placement, thereby reducing spillover in the filtering process.

Current Work: Optimal Placement of MPA Excitation Filaments

In collaboration with Dr. Anjannapa we are extending the techniques used for sensor placement in the Kinematic Filtering scheme to solve the problem of optimal selection of excitation filaments for an ALPEX beam featuring distributed embedded Magnetostrictive Particle Actuators (MPA). The experimental setup is shown in Fig. 1 under Dr. Anjanappa's task progress report. A backward elimination technique is being investigated which involves calculating the effectiveness of each filament on the control performance. Starting from all possible active filament locations the number of locations will be iteratively reduced to the required three. An alternative, globally optimal solution involving simulated annealing is also being investigated. These off-line methods will then be employed in developing a parameter table to enable a real time determination of optimal locations for different patterns of disturbances. It is expected that this method will significantly enhance the effectiveness of the particle actuators for vibration suppression. In the future we plan to investigate a similar procedure to enhance damage detection by optimal selection of auxiliary excitation locations.

Distributed Controllers

P. S. Krishnaprasad and W. P. Dayawansa

Specific Aims

Investigate the problem of designing distributed control laws which respect saturation bounds and hard nonlinearities for effective application of smart materials as the means to enhance structural damping in the presence of a variety of disturbances, including impact loads.

Results

a) Wavelet-based System Identification Schemes:

Typical applications of smart material technology in rotorcraft will contain a large number of actuators and sensors distributed over the rotor and fuselage. Physics-based modeling becomes impractical. The wavelets approach utilizes a priori knowledge of time scales, resonance frequencies etc. to generate an empirical dynamical model for the system.

Our work has resulted in new methodology and software tools for wavelet-based identification of linear systems.

The theoretical basis of our methodology is the observation that there is a large class of stable linear systems, e.g. second order systems with relative degree equal to two, when conceptualized as a mother wavelet forms a basis of the Hardy space H_2 of stable linear systems. This naturally leads to a search for computationally efficient algorithms to obtain finite dimensional approximations to infinite dimensional systems such as flexible structures with a large number of actuators and sensors. We have employed a class of algorithms called projection pursuit algorithms for this purpose.

This methodology has been applied with success to a flexible beam with surface mounted actuators and sensors to derive parsimonious approximate dynamical models. Results have been experimentally validated.

b) Control Laws taking into account Actuator Saturation:

Smart materials in their best forms produce small strains. In order to extract maximum benefits one must deliberately saturate the control elements. This effort investigates the derivation of such control schemes.

Our work has resulted in novel control theories for systems with actuators subject to saturation limits. An experimental set up has been developed to test these theories. A recently acquired software/hardware platform AC100 is being used to develop control laws in software first and implement them in hardware.

Theoretical results obtained include an observer based scheme for stabilizing smart structure systems using control laws that respect saturation bounds.

c) Impact Control Methodology:

There is a variety of control problems of interest to the army, where impulsive forces act as disturbances to a system. Our research aims at developing approximations to impact-induced dynamic models and use them to derive control laws to attenuate impulsive disturbances.

Our work has resulted in an in-depth study of dynamical phenomena induced on flexible structures by impacting objects. We have shown that complex nonlinear dynamical equations that occur in general can be greatly simplified. H_∞ control methodology has extended to the case of impact induced dynamics.

Our work on impact control will have direct relevance to the precision control of gun-turrets, helicopter gun ships, army vehicles traversing rough terrain etc. Work on saturating controllers will have profound consequences for all smart actuator systems, since it allows one to utilize the capabilities of the actuators fully. Identification algorithms are ideally suited for developing dynamical models which are a prerequisite for precision control.

Publications

Q.F. Wei, W.P. Dayawansa and P.S. Krishnaprasad (1994). "Optimal H_∞ Control For Impulsive Disturbances," 1994 Conf. on Information Sciences and Systems, Princeton, March.

Q.F. Wei, P.S. Krishnaprasad, and W.P. Dayawansa (1994). "Approximation of Dynamical Effects Due to Impact on a Flexible Beam," Proceedings of the American Control Conference, American Automatic Controls Council, Phila., pp 1841-1845.

Q.F. Wei, W.P. Dayawansa and P.S. Krishnaprasad (1994). "H_∞ Control For Impulsive Disturbances: A State-Space Solution," American Control Conference, June.

T. Kugarajah, P.S. Krishnaprasad and W.P. Dayawansa (1995). "Identification and Intelligent Control of 2D Smart Composite," To appear. SPIE Conf. on Smart Structures and Materials: Mathematics and Controls of Smart Structures, Feb 26 - March 3, San Diego.

Large Displacement Magnetostrictive-Electrostrictive Actuators

P. S. Krishnaprasad and W. P. Dayawansa

Specific Aims

To investigate the feasibility of using coupled piezoelectric and magnetostrictive devices in electrical resonance to design and build a smart motor prototype.

Results

An extensive analysis has been carried out on this design problem. These include, analysis of a system of coupled nonlinear differential equations, analysis of impact loading, linear approximations, and frequency response analysis etc. Extensive simulations were carried out for expected performance analysis.

A complete design of a motor was done. It was fabricated at the Physics Shop at University of Maryland.

The smart motor is currently being tested.

In the design, priority was given to utilizing off-the-shelf components so as to keep the costs low. Once the current design and prototype are tested thoroughly, we plan to investigate, possibly in collaboration with an industrial partner, prospects for scaling our concept down to the size appropriate for rotorcraft applications.

Publications

R. Venkataraman, P. S. Krishnaprasad, W. P. Dayawansa and J. Loncaric (1995). "Smart Motor Concept Based on Piezoelectric-Magnetostrictive Resonance", In Proceedings of the SPIE Conference on Smart Structures and Materials: Special Conference on Mathematics and Controls of Smart Structures, Feb 26 - March 3, San Diego.

OUTSIDE INTERACTION AND TECHNOLOGY TRANSFER

The following interactions took place with industry, government laboratories and other institutions outside the Smart Structures URI at the University of Maryland:

- Assisted Dr. Frederick Straub of McDonnell Douglas Helicopter Comapny with the building of a full-scale actuator for the Apache helicopter.
- Assisted Dr. David Haas of the David Taylor Naval Research Center in their initiative on "Rotor Head Fault Detection."
- Technology assessment and demonstration of fiber optics system for an aircraft for Lockheed Aeronautical Systems Company (Georgia).
- Assisted Martin Marietta Laboratories (Baltimore, MD) in the development of fiber optic based impact location and energy measurement techniques.
- Assisted Optical Air Data Systems (Bethesda, MD) in the development of an optical fiber LDV system.
- Provided Dr. Norm Coleman of the Army ARDEC at Picatinny Arsenal (New Jersey) with software tools for the identification of impact problems.
- Shared data on magnetostrictive materials with Dr. Mel Goodfriend of Edge Technology Corporation.
- Collaborated with Dr. Verend Zonker of NRL on a study of Zn/Fe/Se thin films.
- Collaborated with Dr. Mike Haase of 3M Company on a study of Zn/Se based films for blue lasers.
- Participated in a study of III/V boron nitrite films with Dr. Dale Partins of GM Research Laboratories.
- Assisted Prof. Van Thompson, Dental Department of UMAB, to characterize a magnetostrictive actuator developed for dental applications.
- Discussed extending electro-rheological fluid models to magneto-rheological fluids and shared existing ER fluid models with Lord Corporation

DEGREES AWARDED

Mr. Christopher Bothwell was awarded the Master of Science in Aerospace Engineering (May 1994) under the supervision of Dr. Inderjit Chopra.

Ms. Kimberly A. Kahl was awarded the Master of Science in Mechanical Engineering (December 1994) for a thesis entitled "Damage Prediction in Continuous Structures Using a Subspace Rotation Algorithm" under the supervision of Dr. James S. Sirkis.

Mr. Gopalakrishna M. Kamath was awarded the Master of Science in Aerospace Engineering (August 1994) for a scholarly paper entitled "Damping Augmentation Using Electro-Rheological Fluids" under the supervision of Dr. Norman M. Wereley.

Mr. Adesh K. Jain was awarded the Master of Science in Mechanical Engineering (August 1994) for a thesis entitled "Failure Analysis of Piezoelectric Ceramics Using Continuum Damage Mechanics" under the supervision of Dr. James S. Sirkis.

Taesung Kim was awarded the Doctor of Philosophy in Material Science (December 1994) for his thesis entitled "A NiTi Microactuator" under the supervision of Dr. Manfred Wuttig.

Mr. Reza Shahidi was awarded the Doctor of Philosophy in Electrical Engineering (May 1994) for a thesis entitled "Active Vibration Damping by Parametric Control" under the supervision of Drs. Krishnaprasad and Dayawansa.

Mr. R. Vekataraman was awarded the Master of Science in Electrical Engineering (December 1994) for a thesis entitled "A Hybrid Actuator" under the supervision of Drs. Dayawansa and Krishnaprasad.

Mr. Curtis Walz was awarded the Master of Science in Aerospace Engineering (May 1994) entitled under the supervision of Dr. Inderjit Chopra.

Qifeng Wei was awarded the Doctor of Philosophy in Electrical Engineering (May 1994) for a dissertation entitled "Modeling and Control of Dynamical Effects due to Impact on Flexible Structures," under the supervision of Drs. Dayawansa and Krishnaprasad.

Capt. David L. Ciminelli was awarded the Master of Science in Mechanical Engineering (December 1994) for a thesis entitled "Extended Range Pseudo-heterodyne Demodulation Using Electrical Phase Characterstics of All-pass Filters" under the supervision of Dr. James S. Sirkis

ABSTRACTS OF PUBLICATIONS AND PRESENTATIONS

Hover Testing of a Smart Rotor with Induced-Strain Actuation of Blade Twist

Peter C. Chen and I. Chopra

To be presented at the 36th AIAA/ASME Adaptive Structures Forum, New Orleans, LA, 12-13 April 1995.

The goal of this research is to develop an individual blade control (IBC) rotor vibration reduction scheme based upon smart structures technology. Blade tip twist amplitudes on the order of 1-2 degrees at N/Rev (where N is the number of blades) are expected to be sufficient to generate airloads which will cancel blade vibrations. This paper presents the hover stand testing results of a dynamically-scaled smart helicopter rotor blade with torsional actuation of blade twist using piezoceramic elements. The smart rotor under development is a six-foot diameter, 1/8-th Froude scale, two-bladed bearingless rotor. The blades are constructed around a rigid foam NACA 0012 airfoil contour and discrete banks of piezoceramic actuators are arranged at ply angles of ±45° on the top and bottom surfaces of the blade and embedded below a conformal fiberglass skin. Accelerometers embedded in the blades are used to determine the tip twist of the blades in rotation. The blade twist and resulting change in rotor lift of various rotor blade configurations are presented in this paper to assess the feasibility of this vibration reduction scheme.

Induced Strain Actuation of Composite Beams and Rotor Blades with Embedded Piezoceramic Elements

Peter C. Chen and Inderjit Chopra

Presented at the SPIE North American Conference on Smart Materials and Structures, Orlando, Florida, 13-18 February 1994.

The objective of this research is to develop a dynamically-scaled (Froude scale) helicopter rotor blade with embedded piezoceramic elements as sensors and actuators to control blade vibrations. A 6 ft diameter 2-bladed bearingless rotor model was built where each blade is embedded with banks of piezoelectric actuators at ± 45° angles with respect to the beam axis on the top and bottom surfaces. A twist distribution along the blade span is achieved through in-phase excitation of the top and bottom actuators at equal potentials, while a bending distribution is achieved through out-of-phase excitation. In order to fix design variables and to optimize blade performance, a uniform strain beam theory is formulated to analytically predict the static bending and torsional response of composite rectangular beams with embedded piezoelectric actuators. Parameters such as bond thicknesses, actuator skew angle and actuator spacing are investigated by experiments and then validated by theory. The static bending and torsional response of the rotor blades is experimentally measured and

correlated with theory. Dynamic torsional and bending responses are experimentally determined for frequencies from 2-120 HZ to assess the viability of a vibration reduction system based on piezo-actuation of blade twist. Although the magnitudes of blade twist attained in this experiment were small, it is expected that future models can be built with improved performance.

Torsional Actuation with Extension-Torsion Composite Coupling and Magnetostrictive Actuators

Christopher M, Bothwell, R. Chandra and I. Chopra

Presented at the 35th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Paper No. 94-1760, Hilton Head, South Carolina, 18-21 April 1994.

This paper presents an analytical cum experimental study of using magnetostrictive actuators in conjunction with an extension-torsion coupled composite tube to actuate a rotor blade trailing edge flap to actively control helicopter vibration. Thin-walled beam analysis based on Vlasov theory is used to predict the axial force-induced twist and extension in the composite tube. $[20/-70]_{2s}$ graphite-epoxy as well as $[20/-70]_s$ and $[11]_2$ kevlar-epoxy tubes were fabricated using an autoclave molding technique. The tubes were tested under static mechanical loads, and tip twist and axial extension were measured by means of a laser optical system and strain gages respectively. The tubes showed good correlation between theory and experiment for the external load case. The magnetostrictive actuator/composite tube systems were then assembled and tested. The $[20/-70]_{2s}$ graphite-epoxy tube system exhibited 0.03° of tip twist in both tension and compression, while the $[20/-70]_s$ kevlar-epoxy tube resulted in a tip twist of 0.089° in tension and 0.102° in compression. The $[11]_2$ kevlar-epoxy tube system generated the most twist, 0.19° in tension and 0.20° in compression. The kevlar-epoxy systems showed good correlation between measured and predicted twist values. Further parametric studies were performed to determine the important design variables that would result in maximum induced twist and actuator force.

Design of High Force High Displacement Actuators for Helicopter Rotors

Dhananjay K. Samak and Inderjit Chopra

Presented at the 1994 SPIE Conference on Smart Materials and Structures, Orlando, FL, 13-18 February 1994.

This paper presents the development of electromechanical actuators based on the concept of mechanical amplification with piezo and electrostrictive stacks as drivers to achieve high force and high displacement actuation. The actuators were designed for two different applications. The first actuator with piezo stack was developed to actuate a "Flaperon" which consisted of a small movable surface to trip the boundary layer, located on the top surface of a wing model with span and chord each of 12 inch and of

NACA 0012 airfoil. The actuator was designed to produce 8 lbs of force with peak displacement of 10 mils at a maximum frequency of 40 Hz. The second actuator with electrostrictive stack as a driver was designed to move a leading edge droop flap hinged at 25% chord of a wing model with span of 8 inch, chord of 4 inch and of VR-12 airfoil. This actuator was designed to produce 8.5 lbs of force with peak displacement of 10 mils at a maximum frequency of 45 Hz. Experiments were performed on both stacks to evaluate their important characteristics such as block force, free displacement, stiffness that were essential in the design of the actuators. The results showed that the block force obtainable from piezo stack was higher and that of electrostrictive stack was lower than that specified by the respective manufacturers while the free displacements are about the same. The dynamic response of the actuators over a frequency range of 33 Hz was evaluated. Results showed that the actuation force of 7 lbs of actuator force was obtainable in both the cases with flaperon actuator producing 15 mils of dynamic displacement at 15 Hz and droop flap actuator producing about 6 mils of displacement at 16 Hz. The results were inconclusive beyond 16 Hz due to the setup resonance. Droop flap actuator did not achieve the desired performance because the design calculations were based on block force listed by the manufacturer which was about 20% higher than the measured value. This led to the conclusion that before design process begins, the stack alone performance should be carefully measured to achieve required performance. Thus, a simple actuator based on mechanical amplification concept could be effectively designed to produce high force and high displacements.

Dynamic Response of Composite Beams with Induced-Strain Actuators

Ramesh Chandra

Presented at the 1994 SPIE Conference on Smart Structures and Materials, Orlando, FL, 13-18 February 1994.

This paper presents an analytical-experimental study on dynamic response of open-section composite beams with actuation by piezoelectric devices. The analysis includes the essential features of open-section composite beam modeling, such as constrained warping and transverse shear deformation. A general plate segment of the beam with and without piezoelectric ply is modeled using laminated plate theory and the forces and displacement relations of this plate segment are then reduced to the force and displacement of the one-dimensional beam. The dynamic response of bending-torsion coupled composite beams excited by piezoelectric devices is predicted. In order to validate the analysis, kevlar-epoxy and graphite-epoxy beams with surface mounted piezoceramic actuators are tested for their dynamic response. The response was measured using accelerometer. Good correlation between analysis and experiment is achieved.

Development of ER-Fluid Based Actuators for Rotorcraft Flexbeam Applications

Gopalakrishna M. Kamath and Norman M. Wereley

To be presented at the 1995 SPIE Conference on Smart Structures and Materials, 26 February to 3 March 1995, San Diego, CA.

A numerical study of electrorheological (ER) dampers is presented. Two models, the Newtonian and the Bingham plastic models are used to characterize the ER fluid behaviour. Damping performance of two damper configurations, the Moving Electrode and the Fixed Electrode configurations, is studied. The effects of electrode gap sizes, the field strength and the ER fluid model used are quantified. The study provides a basis for design of ER-fluid based dampers.

Distributed Damping of Rotorcraft Flexbeams Using Electrorheological Fluids

Gopalakrishna M. Kamath and Norman M. Wereley

To be presented at the AIAA/ASME Adaptive Structures Forum, 13-14 April 1995, New Orleans, LA.

A non-linear model is developed that accurately simulates the dynamic characteristics of an electrorheological fluid. Two linear models, a viscous model and a viscoelastic damping model are combined using non-linear shape functions of strain rate. The 3-parameter fluid model is used to represent the viscoelastic behaviour. The model parameters are estimated for different values of electric fields using the least square technique. The model developed here correlates well with data presented in the literature.

Passive Damping Techniques for Composite Rotorcraft Flex Beams

Clifford B. Smith and Norman M. Wereley

To be presented at the AIAA Structures, Structural Dynamics, and Materials Conference. 13-14 April 1995, New Orleans, LA.

An experimental study of passive damping in rotating composite I-beams is presented. Damping is augmented in a Gr/Ep I-beam using a co-curable visco-elastic material layer in the flanges of the I-beam. This study examines the effects of variable visco-elastic material thickness in the flange in improving passive damping performance. Experimentation is carried out in both a non-rotating, and rotating condition in the vaccuum chamber.

Active Constrained Layer Damping for Rotorcraft Flex Beams

Subhobroto Nath and Norman M. Wereley

To be presented at the AIAA Adaptive Structures Forum. 13-14 April 1995, New Orleans, LA.

Hingeless and bearingless rotors are prone to air resonance and ground resonance instabilities, which can be mitigated through damping augmentation. The flex beam in these rotors is a candidate structure for implementing active constrained layer damping (ACLD). The flex beam can be modeled as a beam in the cantilevered condition with a tip force representing the structural and aerodynamic loads due to the rotor blade dynamics. The objective of this study is to develop a control model for a fully treated ACLD flex beam where the shear is modeled using the complex shear modulus. The model developed here is based on a elastic-viscoelastic-elastic beam model, where the steady state forced response is obtained using a progressive wave solution. The open-loop transfer function from the piezo to beam states, as well as the sensitivity transfer function from the tip force to beams states, can be computed using this modeling approach. These transfer functions are in a useful form for single-input single-output feedback controller synthesis.

Active Damping of a Flexible Beam Using ER Fluid Actuators

Norman M. Wereley

Presented at the AIAA/ASME Adaptive Structures Forum, 21-22 April 1994, Hilton Head, SC.

Advanced rotor systems including hingeless and bearingless rotors have air and ground resonance instabilities due to coalescence of low frequency rotor modes with landing gear and fuselage modes, respectively. The rotor blade is connected to the rotor hub via a flexure or flexbeam. The modal coalescence is of difficulty due to the lack of a clear hinge in these advanced rotor systems. We are currently exploring the mitigation of this modal coalescence through the use of active damping techniques and electro-rheological fluid technology. An emulation of a flexbeam was fabricated from a glass epoxy composite, and filled with ER fluid, to determine feasibility of using ER fluid for active damping of the flexbeam.

Unsteady Lift of a Flapped Airfoil by Indicial Concepts

J. Gordon Leishman

Journal of Aircraft, March-April, 1994.

A practical method is described for computing the unsteady lift on an airfoil due to arbitrary motion of a trailing-edge flap. The result for the incompressible case is obtained in state-space form by means of Duhamel superposition and employing an improved exponential approximation to Wagner's indicial lift function. For subsonic compressible flow, the indicial lift at small values of time due to impulsive trailing-edge flap deflection is obtained from linear theory in conjunction with the aerodynamic reciprocal theorems. These results are used with experimental results for the oscillating airfoil case to obtain complete exponential approximations for the indicial response due to impulsive flap deflection. The final result for the unsteady lift due to an arbitrary flap motion in subsonic flow is obtained in state-space form. Numerical results and comparisons with experimental data are shown.

Elastic and Anelastic Properties of CVD Epitaxial 3C-SiCJ

C.M. Su, A. Fekade, M. Spencer and Manfred Wuttig

Appl. Phys. 77, 1432 (1994)

Chemical vapor deposited (CVD) 3C-SiC films were micromachined into free standing cantilevers and their anelastic and elastic properties were determined by a vibrating reed technique. Despite a high density of defects epitaxial 3C-SiC exhibits extremely high mechanical Q which is essential for resonator sensors and actuators. An anelastic relaxation peak was found with an associated activation energy of 0.94 eV. Doping caused splitting of this peak. The mechanism of the mechanical relaxation peak is discussed in relation to defect movement under stress. Young's modulus was found to be 694 GPa un-doped samples and reduced to 474 GPa for p-doped 3C-SiC.

Switching Effect of NiTi Shape Memory Alloy Films

Q. Su, T. Kim and M. Wuttig

MRS Symposium Proceedings, Vol 360, Materials for Smart Systems, 1995.
In Press.

The mechanical properties of Ni50Ti50 deposited on Si and 3C-SiC substrates were studied focussing on the interaction of the film and substrate. This interaction determines the transformation characteristics through interface accommodation and mechanical constraints exerted by the substrate stiffness. Substrate stiffness, controlled by the film/substrate thickness ratio, was found to have a substantial influence on the output energy of the film/substrate composite. A switch type composite based on this knowledge was fabricated and tested.

Thermo-Magneto-Mechanical Properties of Thin Film Terfenol-D

M. Wuttig, H. Zheng and Q. Su

MRS Symposium Proceedings, Vol 360, Materials for Smart Systems, 1995. In Press.

The thermo-mechanical properties of Terfenol-D thin films deposited on Si substrates were studied by static and dynamic measurements of film/substrate composite cantilevers. The Curie transition, E effect and mechanical damping of the film were measured simultaneously. The stress in the film was controlled by annealing below the recrystallization temperature and determined to vary from -500 MPa, compression, in as deposited films to +480 MPa, tension, in annealed films. The Curie temperature shifts from 80°C to 140°C as the tension increases while the structure of the film remains amorphous. The stress change induced by annealing also drastically effects the film's damping characteristics. The E effect of the amorphous material, about 20%, was used to estimate the magnetostriction.

In-Process Evaluation of Kinetic Energy of Sputter Depositing Atoms Using Multijunction Thermal Converters

Quanmin Su, D. X. Huang and, Manfred Wuttig,

MRS Symposium Proceedings: 1994 Fall Meeting. In Press.

The kinetic energy of Au atoms was evaluated during sputter deposition of Au films using a multijunction thermal convertor (MJTC). The elastic strain energy of the deposited film was simultaneously measured by a high resolution vibrating membrane technique. For the evaluation the flux of Au atoms was treated as an energy flux irradiating a membrane connected to an infinite heat sink. The steady state temperature rise of this membrane under irradiation was used to convert to the kinetic energy of the atomic flux of known deposition rate. The kinetic energy of the sputter depositing Au flux was determined to be in the range of 5 to 18 eV. Only a fraction of it, of the order of 10-4, is converted into mechanical energy manifesting itself as film stress. The results demonstrate the possibility of using MJTCs as kinetic energy monitors during thin film deposition.

Substrate Stress Controlled Magnetic Domains in Amorphous Terfenol-D Films

Quanmin Su, Y. Zheng, A. Roytburd and Manfred Wuttig

Journal of Applied Physics Letters. In Press.

Magnetic force microscopy of amorphous compressed Terfenol-D, Fe2(Dy0.3Te0.7)1 , films of micron thickness on both crystalline Si and glassy silica shows that their ferromagnetic domain structure is one dimensional and periodic. On Si the structure is aligned with respect to the easy elastic direction of the substrate. The square of the domain period is proportional to the thickness of the film. All facts indicate that the domain morphology in these films is determined by a substantial elastic contribution to the domain wall and film/substrate interaction energies.

Feedforward Active Interior Noise Control

B. Balachandran, A. Sampath, and J. Park

To be presented at the 1995 SPIE Conference on Smart Structures and Materials, San Diego, California, Feb. 26 - March 3, 1995. SPIE Paper No. 2443-73.

Analytical and experimental studies undertaken for controlling noise in the interior of a three-dimensional enclosure with a flexible boundary are presented. The rigid boundaries are constructed from acrylic material, and the flexible boundary is constructed from aluminum material. Noise generated by an external speaker is transmitted into the enclosure through the flexible boundary and active control is realized by using Lead Zirconate Titanate (PZT) piezoelectric actuators bonded to the flexible boundary. Condenser microphones are used for noise measurements. For panel and cavity controlled modes, analog controllers based on feedforward schemes using acoustic error signals are developed and discussed.

Active Structural Acoustic Control of Bandlimited Disturbances

A. Sampath and B. Balachandran

Presented at (Proceedings of) SPIE 1996 NorthAmerican Conference on Smart Structures and Materials, San Diego, California, Feb. 26-29, 1996; Paper No. 2717-36, vol. 2717, pp. 422-433.

Experimental investigations into the control of noise in the interior of a three-dimensional enclosure with a flexible wall are presented for harmonic and multiple frequency disturbances. Lead Zirconate Titanate (PZT) patches mounted on the flexible wall are used as actuators and condenser microphones are used as acoustic sensors in a digital feed forward control scheme. The control system is effective in identifying the dominant resonances and achieving significant noise reduction for the dominant modes. Based on the studies on the effect of actuator redundancy on noise reduction, it is found that less noise reduction is achieved when there are more number of actuators than sensors. Modal spillover is also observed in some of the controlled cases.

Structural Intensity Calculations for Active Control of Plate Vibrations

M. Jin and B. Balachandran

Presented at (Proceedings of) SPIE 1996 North American Conference on Smart Structures and Materials, San Diego, CA, Feb. 26-29 1996; Paper No. 2717-34, vol. 2717, pp. 399-408.

Numerical studies undertaken to determine the structural intensity for active vibration of plates bonded with piezoceramic patches are presented. The formulation, which is based on finite-difference schemes, allows for thin isotropic plates with general boundary conditions. Active and reactive intensities are computed for the different cases, in which the considered plate is excited by a planar sound field and/or one or more piezoceramic patches. The numerical results indicate the importance of considering reactive intensities for active vibration control applications.

Active Control of Transmission of Bandlimited Disturbances into a Three-Dimensional Enclosure

A. Sampath and B. Balachandran

Proceedings of the ASME Aerospace Division, J. C. I. Chang, J. Coulter, D. Brei, D. Martinez, W. Ng, and P. P. Friedmann, eds. 1996 ASME International Mechanical Engineering Congress and Exposition, Atlanta, Georgia, Nov. 17-22, 1996.

Experimental investigations into active control of bandlimited noise transmitted into the interior of a three-dimensional enclosure with a flexible wall are presented. In the different experiments, the frequency range of the bandlimited disturbance is chosen to encompass structural and/or enclosure resonances. The rigid boundaries of the enclosure are constructed from acrylic material, and the flexible boundary clamped along all the edges is constructed from aluminum material. Lead Zirconate Titanate (PZT) patches mounted symmetrically on the flexible wall are used as actuators. Polyvinylidene fluoride (PVDF) film patches mounted on the flexible wall are used as vibration sensors, and condenser microphones placed inside and outside the enclosure are used as acoustic sensors. Digital feedforward control schemes based on filtered-x gradient descent algorithms are implemented in the experiments to minimize a chosen performance function. Different performance functions are examined, and the results obtained in the corresponding cases are compared . It is observed from the experiments conducted thus far that better noise reduction results are obtained when only acoustic sensors are used than when either vibration sensors or a combination of acoustic and vibration sensors is used.

Studies on Active Acoustics Control

B. Balachandran and A. Sampath

Presented at the Far East and Pacific Rim Symposium on Smart Materials, Structures and MEMS, Bangalore, India, Dec. 11-14, 1996.

Analytical and experimental investigations into active control of sound fields within a three-dimensional enclosure are presented for tonal and bandlimited disturbances. Lead Zirconate Titanate (PZT) patches mounted on the flexible wall of the enclosure are used as distributed actuators, and polyvinylidene fluoride (PVDF) film mounted on the flexible wall and condenser microphones are used as sensors. The sensors and actuators are used in a digital, adaptive feedforward control scheme to realize ``local" noise and vibration control. For tonal disturbances, the developed analytical model is found to yield results that are in good agreement with the experimental observations. Different cases of bandlimited disturbances are considered in the experiments. These cases include multiple panel and/or enclosure resonances. For bandlimited disturbances, the control scheme is found to be effective in identifying the dominant resonances and realizing significant noise reductions at the dominant modes. However, the local noise reductions realized for bandlimited disturbances are not as high as those realized for tonal disturbances. Issues such as performance functions are also explored in the investigations.

Active Hybrid Control of Plate Vibrations

B. Balachandran, A. Sampath, and M. Padmanabhan

Presented at the Far East and Pacific Rim Symposium on Smart Materials, Structures and MEMS, Bangalore, India, Dec. 11-14, 1996.

In this work, which is motivated by recent developments in active structures, control of vibrations of a thin isotropic plate subjected to different spatial disturbance fields is considered. The plate is simply supported along all edges, and the plate vibrations are sensed by using point sensors. The control effort is realized by using piezoceramic patches as distributed actuators. An appropriate mechanics based model is used for the plate-piezo system, and this model is reduced to a finite-dimensional state-space model through a Galerkin projection. This model is used in the numerical studies. Exploiting the advantages of using a direct velocity feedback scheme for controlling broadband disturbances and an adaptive feed forward scheme for controlling narrowband disturbances, a hybrid active scheme is synthesized for controlling the vibrations of a plate subjected to different combinations of temporal disturbances. Although many efforts have been undertaken for controlling plate vibrations, active hybrid schemes based on distributed actuators have not been considered previously. In this study, numerical studies indicate the advantages of an active hybrid scheme to handle different types of temporal disturbances.

Active Interior Acoustics Control of Bandlimited Disturbances

Sampath and B. Balachandran

Proceedings of the SPIE 1997 North American Conference on Smart Structures and Materials, San Diego, California, Mar. 3-6, 1997.

Extensions of our previous analytical and experimental investigations into active control of bandlimited disturbances in a three-dimensional enclosure are presented. The frequency range of the bandlimited disturbance is chosen to encompass structural and/or enclosure resonances. Distributed piezoceramic actuators and distributed polyvinylidene fluoride (PVDF) sensors are mounted on one of the enclosure boundaries. Condenser microphones are used as acoustic sensors inside and outside the enclosure. A mechanics based state-space model is developed for local vibration control on an enclosure boundary and/or local noise control inside the enclosure for bandlimited disturbances. Different performance functions are considered in this study, and they are minimized by using digital feedforward control schemes based on filtered-U gradient descent algorithms. Analytical predictions and experimental observations are compared and discussed.

Active Control of Noise Transmission Through Flexible Panels with Constrained Layer Damping

B. Balachandran, A. Sampath and C. W. Ahn

Presented at the Eleventh VPI & SU Symposium on Structural Dynamics and Control, Blacksburg, VA, May 12-14, 1997.

A collection of results obtained in experimental investigations into active control of noise transmission through a flexible panel into a three-dimensional enclosure will be presented. These investigations are closely related to our previous work. The flexible panel, which forms one of the boundaries of the enclosure, is treated with viscoelastic layer treatments at discrete spatial locations. Each viscoelastic layer is sandwiched between the flexible panel and a piezoceramic patch. The piezoceramic patches are used as actuators and condenser microphones located inside and outside the enclosure are used as acoustic sensors. The sensors and actuators are used in a digital, adaptive feed-forward control scheme to realize ``local'' noise control. Two types of viscoelastic treatments are considered and the effectiveness of the different constrained-layer treatments for tonal and bandlimited disturbances are studied. Some of the band-limited disturbances are chosen to include one or more structural and/or enclosure resonances. Comparisons are also made with results that were previously reported by the authors.

Moire' Analysis of Thick Composites with Embedded Optical Fibers

J. S. Sirkis and H. Singh

Experimental Mechanics. Vol.34, No.4, Dec. 1994.

Moire' interferometry is used with Fourier transform fringe analysis to investigate the strain fields in a region local to 125 µm uncoated silica optical fibers embedded in a quasi-isotropic graphite/PEEK thick composite compression specimens. Analysis of several regions in several specimens showed no measurable strain concentrations resulting from the embedded optical fibers, even though the optical fibers clearly alter the local microarchitecture of the host material system.

Direct Extraction of Phase Gradients From Fourier Transform and Phase-Step Fringe Patterns

H. Singh and J. S. Sirkis

Applied Optics. Vol. 33. No. 22, pp. 5016-5020, 1994.

An approach to directly computing pixel-by-pixel gradients of optical phase from digitally encoded Fourier transform or phase-stepped fringe patterns is described. This approach can be classified as a phase unwrapping but is really a sine-cosine demodulation technique that finds its roots in the differential cross multiplier phase demodulation technique commonly used by the optical fiber sensor community. This technique is algorithmically simple, does not rely on computing the arctangent, and therefore is not subject to some of the limitations of the standard phase unwrapping methodologies. The proposed phase gradient technique is demonstrated by calculating strain fields from moire' interferometric fringe patterns.

Evaluation of Integrated Optic Modulator-Based Detection Schemes for In-Line Fiber Etalon Sensors

H. Singh, J. Sirkis, J. Andrews, and R. Pulfrey,

J. of Lightwave Technology, 1995. In Press.

This paper compares three classes of demodulation schemes for interpreting the static and dynamic response of In-Line Fiber Etalon (ILFE) sensors. Each demodulation scheme employs path matched differential interferometry and an unbalanced integrated optic Mach-Zehnder interferometer as a readout interferometer. Active homodyne, synthetic-heterodyne and two types of pseudo-heterodyne based demodulators are evaluated. In the results presented here, signals generated by the ILFE ranging from quasi-static to about 100Hz were recorded and compared with the signals generated by a resistance strain gage, and were found to be in good agreement.

In-Line Fiber Etalon (ILFE) Fiber Optic Strain Sensor

J. Sirkis, T. A. Berkoaff, R. T. Jones, A.D. Kersey, E. J. Friebele, and M. A. Putnam

J. of Lightwave Technology, 1995. In Press.

This paper describes an optical fiber interferometer that uses a short segment of silica hollow-core fiber spliced between two sections of single mode fiber to form a mechanically robust in-line optical cavity. The hollow-core fiber is specifically manufactured to have an outer diameter that is equal to the outer diameter of the single mode lead fibers, thereby combining the best qualities existing intrinsic and extrinsic Fabry-Perot sensors. Uniaxial tension and pure bending strength tests are used to show that the new configuration does not diminish the axial strength of bare fiber and reduces the bending strength by 17 percent at most. Similar tests confirm that the fiber sensor has 1.96 percent strain to failure. Axisymmetric finite element analysis is used to investigate the reliability of in-line etalon when it is embedded in a typical thermoset composite cure conditions, and parametric studies are performed to determine the mechanically optimal cavity length. The fiber optic sensor is tested using low coherence interferometry with pseudo-heterodyne demodulation under strain and temperature fields. The strain response compares well with resistance strain gages, and the temperature tests confirm the low thermal apparent strain of this sensor.

Dual-Parameter Optical Fiber Sensor

H. Singh and J. S. Sirkis,

To be presented at the 1995 SPIE Conf. on Smart Stuctures and Materials: Smart Sensing, Instrumentation and Processing, 26 Feb. to 3 March 1995, San Diego, CA.

In this paper we have presented a sensor system capable of measuring two parameters on a surface mounted beam. We have used an In-Line Fiber Etalon (ILFE) and an Intrinsic Fabry-Perot (IFP) sensor to capture two parameters at a single point. This sensor with gage length of about 200 μm can be used to determine the axial strain and temperature on a beam or can be embedded in composite material to determine two strain components. The two sensor signals which travel in the same fiber are discerned using coherence based multiplexing schemes. Three tests are performed with the sensor mounted on a cantilevered beam to demonstrate the concept. In the first test, the beam is subjected to simple vibration and the phase strain model is used to calculate the strains from the two sensors. In the second test the beam is given only thermal loading, and in the third test, the beam is subjected to a combination of both thermal and mechanical loading.

Cross-Talk and Noise Issues in Coherence Multiplexed In-Line Fabry Perot Etalon (ILFE) Strain Sensor

Harmeet Singh and James S. Sirkis

To be presented at the 1995 SPIE Conf. on Smart Stuctures and Materials, 26 February to 3 March 1995, San Diego, CA.

In this paper we have investigated the cross-talk and noise issues that arise in serial multiplexing of In-Line Fiber Etalon (ILFE) strain sensors using three different topologies. First, the broadband source is numerically modeled to preserve all the artifacts in the line structure. Second, the effect of beam expansion in the non-guiding ILFE cavity is investigated. The two models are combined to calculate the fringe contrast, signal and background power, the shot-noise and cross-talk noise in the system. Also the signal extinction is studied as a function of mismatch between the ILFE gagelength and path-matching interferometer gagelength. Finally, suggestions are made to enhance the fringe contrast in ILFE based systems.

Sub-Millimeter Gage-Length Fiber Optic Sensor

H. Singh and J. S. Sirkis

(Invited) Society for Experimental Mechanics Spring Conference, June 1995, Grand Rapids, MI.

This paper is an overview of the novel In-Line Fiber Etalon (ILFE) sensor and associated demodulation schemes developed to measure strains with a large bandwidth and high dynamic range. This sensor is highly localized, is shown to possess negligible sensitivity to temperature drifts and is immune to transverse loading. We have used two optical configurations to interpret the ILFE sensor response, the first using an integrated optic chip (IOC) and the second using a PZT stack. We have demonstrated high bandwidth/dynamic range measurement capability using pseudo-heterodyne, synthetic-heterodyne, active-homodyne, and single channel phase tracking schemes for the optical signal demodulation. Finally, we have shown that we can use the ILFE sensor in tandem with an intrinsic Fabry-Perot sensor (IFP) to constuct a localized sensor that is capable of measuring the strain and temperature at one point simultaneously.

Location and magnitude of impact detection in composite plates using neural networks

R.T. Jones, J.S. Sirkis, E.J. Friebele, A.D. Kersey

To be presented at the 1995 SPIE Conference on Smart Structures and Materials, 26 Feb. to 3 March 1995, San Diego, CA.

A method of determining the location and extent of impact induced damage in isotropic plates is investigated numerically and experimentally. A computer simulation of impact to this model plate provided information in the form of frequency response data and strain traces. These data sets were inputs into two different backpropagation neural networks. The first neural network uses FFT of strain data, which is split into real and imaginary parts and integrated over the first ten harmonic natural frequencies for each of four sensors (8 inputs into neural network). This particular network has been trained on a set of 63 simulated impacts, with the network solving for the location of impact sites within an average of 8 millimeters per impact. The second network uses the same FFT of strain data (8 inputs), but additionally uses the impact coordinates as inputs (total of 10 inputs). The network has been trained on a set of 800 simulated impacts, and solves for magnitude of the impact events with an average error of 7.08%. Experimental impact location determination has been accomplished by using a set of four strain gage sensors mounted in the corners of the isotropic aluminum plate. Data from these sensors were post processed as mentioned above, and used to train a backpropagation neural network. A twenty impact subset of a 72 impact grid was trained to locate impacts with an average RMS error of 1.019 radial centimeters.

Model of Transverse Impact Dynamics For The Design of Impact Detection Methodologies

J.K. Shaw, J. S. Sirkis, E.J. Friebele, R.T. Jones, A.D. Kersey

Submitted to the *AIAA Journal*,

A closed form analytical description of the deformation in a fully clamped, homogeneous and isotropic rectangular plate subjected to transverse impact is presented. This solution is developed for use in the design of impact location and magnitude measurement methodologies. The solution is used to design two artificial neural network-based impact location techniques.

Development of an Impact Detection Technique Using Optical Fiber Sensors and Neural Networks

J. Sirkis, J. Shaw, T. Berkoff, A. Kersey, E. Friebele, E., and R. Jones

Presented at the 1994 SPIE Conf. on Smart Structures and Materials, Smart Sensing, Processing and Instrumentation, SPIE, Vol. 2191, pp. 158-165.

This paper describes an ongoing effort to develop techniques capable of locating the position of space debris impacts and to quantify the strain energy absorbed by the space structure as a result of these impacts. The techniques under development use optical fiber sensors and neural networks as the primary sensor and decision making components. To date, this project has resulted in the development of 1) a mathematical model of plate impact dynamics for use in sensor and neural network paradigm development, 2) a sensor demodulation system specifically designed for moderate impact energies, 3) several neural network paradigms with the potential to locate impacts, and 4) a test configuration to experimentally confirm the proposed paradigms.

Direct Extraction of Phase Gradients From Fourier Transform and Phase-step Fringe Patterns

H. Singh and J. S. Sirkis

Applied Optics, 1995. In Press.

An approach to directly computing pixel-by-pixel gradients of optical phase from digitally encoded Fourier transform or phase-stepped fringe patterns is described. This approach can be classified as phase unwrapping but is really a sine-cosine demodulation technique that finds its roots in the differential cross multiplier phase demodulation technique commonly used by the optical fiber sensor community. This technique is algorithmically simple, does not rely on computing the arc tangent, and therefore is not subject to some of the limitations of standard phase unwrapping methodologies. The proposed phase gradient technique is demonstrated by calculating the strain field from moire' interferometric fringe patterns.

Smart Structures and Materials Research at the University of Maryland

J. S. Sirkis

Science of Machine, 46 (1), pp. 33-37, 1994. (in Japanese).

The University of Maryland in the United States of America has a long standing research program to develop and apply smart materials and structures technology. This research program started in 1988 with one faculty member under the sponsorship of the National Science Foundation, and has since grown to include twenty faculty members with participation from Aerospace Engineering, Mechanical Engineering, Civil Engineering, Materials Science Engineering and the Institute for Systems Research.

The University is recognized as a dynamic research team that emphasizes the cross-disciplinary research that is so critical to the successful development of smart materials and structures. This interdisciplinary philosophy has attracted sponsored programs from eighteen U.S. companies, government laboratories, and state and federal funding agencies. The smart structures and materials programs ongoing at the University range from improved rotorcraft dynamics to mitigation of earthquake damage in civil structures, and includes the development of transducer, actuator, and manufacturing enabling technologies. This article describes the smart materials and structures philosophy adopted by the University of Maryland research team, and then describes some of the ongoing research programs.

Finite Element Modeling of Multi-Functional Composites with Embedded Magnetostrictive Devices

K. S. Kannan and A. Dasgupta

Presented at the 1994 ASME Winter Annual Meeting. AD-Vol. 45/MD-Vol. 54, pp. 21-28, Chicago, IL.

When distributed as microscale devices in a host, magnetostrictives can act as distributed sensors in multi-functional composites capable of cradle-to-grave self-monitoring. This is often termed the "converse" effect. Magnetoelastic interactions in a magnetostrictive material are complicated by nonlinear couplings between the magnetic and mechanical differential equations governing these interactions and in the constitutive relations. In the past, the authors have proposed a nonlinear variational principle and a linearized three-dimensional finite element scheme to model magnetostrictive mini-actuators where the "direct" effect was presented. In this paper, the "converse" effect in magnetostrictive sensors are presented. Typical applications of these devices would be in multi-functional composites capable of sensing residual stresses and operational loads throughout the life cycle.

Effective Properties of 1-3 Piezocomposites Using Eigenstrain Method and Mori-Tanaka Scheme

A.K. Jain, A.A. Alghamdi, A. Dasgupta, and J.S. Sirkis

Proceedings of the ASME Winter Annual Mtg. 1994, AD-Vol.45/MD-Vol.54, pp. 67-73.

The focus of this paper is to obtain the effective properties of a 1-3 piezocomposite consisting of an infinitely large isotropic host with piezoceramic (PZT) cylinders embedded along the thickness. The elastic and electric fields inside PZT cylinders are obtained using Green's function formulation. The Mori-Tanaka method is used to predict the effective properties of the 1-3 composite including elastic, piezoelectric, and dielectric constants, as functions of the PZT volume fraction.

Experimental Investigation of Adaptive Beam with Embedded Devices

A.A. Alghamdi and A. Dasgupta

31st Annual Technical Meeting of Society of Engineering Science, Texas A&M University, College Station, Texas, October 10-12, 1994.

In this paper we are presenting the experimental dynamic response of an adaptive beam containing embedded mini-devices (sensors and actuators). The specimen used is a cantilever beam made of Alplex plastic as host material and PZT-5H as active devices for sensing and actuation. The experimental setup and results are presented and discussed. The capability of mini-actuators to change the dynamical behavior of the adaptive beam is demonstrated through adaptive stiffening and adaptive damping examples.

Nonlinear Finite Element Scheme for Modeling the Magneto-elastic Response of Magnetostrictive Smart Structures

K. S. Kannan and A. Dasgupta

Presented at the 1994 North American Conference on Smart Structures and Materials, Orlando, Florida, February 1994.

A variational statement of the nonlinear boundary value problem of magneto-mechanical interactions in magnetostrictive materials is presented. Some of the complexities arising out of the nature of these interactions are pointed out. A finite element code developed on the basis of a linearized version of the above variational statement is used to model the behavior of an idealized magnetostrictive actuator. The strong influence of coupling constants on the induced magnetic field is demonstrated through our coupled finite element analysis. Errors that are possible in uncoupled analyses are illustrated and the need for fully coupled analyses of general two or three dimensional actuator configurations is brought out.

Finite Element Scheme for Modeling the Magneto-elastic Response of Magnetostrictive Smart Structures

K. S. Kannan and A. Dasgupta

Presented at ICIM '94, Williamsburg, Virginia, June, 1994.

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Transient Response of an Adaptive Beam with Embedded Piezoelectric Microactuators

A. Dasgupta and A.A. Alghamdi

Presented at the 1994 SPIE Conference on Smart Structures and Materials, Orlando, Florida, February 1994.

The transient response and the damping of a cantilevered adaptive beam are explored in this paper. The adaptivity of the beam comes from embedded piezoelectric actuators which are used to enhance the damping of the beam. The dynamic model is based on Hamilton's variational principle and the interactions between the beam and the devices are modeled using Eshelby's equivalent inclusion method. The Rayleigh-Ritz technique is used to obtain the approximate behavior of the structure.

Extended Variance-Based Techniques for Sensor Location in Modal Identification

Frederick A. Tasker and Chinchao Liu

Presented at the AIAA Dynamic Specialists Conference, Hilton Head, South Carolina, 21-22 April 1994.

Methods of sensor placements based on standard criteria on the covariance matrix of estimated modal response are presented. The methods use the backward elimination approach resulting in an efficient method of obtaining the required number of sensors. A framework which permits easy extensions to several criteria is presented. Two methods, one to minimize the maximum variance and the other to minimize the variance of a subset of modes were studied. The methods were found to be effective in choosing locations which minimize these criteria. The effect of weighting columns of the modal matrix was investigated and it was shown that a small weight emphasizes the contribution of the associated mode in the sensor location process.

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Identification of Nonlinear Helicopter Rotor Structural Dynamics

Frederick A. Tasker and Zhengchen Yu

Presented at the 35th AIAA/ASME/AHS/ASCE Structural Dynamics, Structures, and Materials Conference, 18-20 April 1994.

An identification methodology is presented for identifying rotor parameters from nonlinear transient response. The identification model is developed using finite elements in space with approximation of distributed parameters and finite elements in time. Response sensitivities are efficiently calculated from the resulting multi-stage model and used in a quasilinearization identification scheme. It is assumed that modal responses are obtained using multiple sensors in a kinematic filtering scheme to permit modal reduction. The method is validated via numerical simulations of coupled flap and lag bending motion of a rotating blade in vacuum. It was found to be effective in identifying unknown parameters. The method also efficiently accommodates multiple erroneous initial conditions when using several sets of transient responses.

A Theoretical and Experimental Study of Magnetostrictive Mini Actuators

M. Anjanappa and J. Bi

Journal of Smart Materials and Structures, Vol. 3, No. 2, pp. 83-91.

Magnetostrictive mini actuator (MMA), with its unique characteristics such as large strain, high force and high energy density, is potentially a new class of actuator most suitable for distributed actuator applications such as vibration control of smart structures. This paper presents a theoretical framework, validated experimentally, to develop MMA and its feasibility for vibration control. Based on two dimensional thermal analysis, the general form of thermoelastic mathematical model for characterizing the Magnetostrictive-based actuators is proposed and experimentally validated. Thermal effects, at other than initial state, are shown to have significant effect on attainable strain and force of MMA. Experimental results show that the MMA has a good static and dynamic performance, and is suitable for applications in smart structures.

Magnetostrictive Mini Actuators For Smart Structure Applications

M. Anjanappa and J. Bi

Journal of Smart Materials and Structures. In Press.

This paper investigates the feasibility of using embedded magnetostrictive mini actuators(MMA) for smart structure applications, such as vibration suppression of beams. A cantilever beam, embedded with MMA and subjected to free vibration was chosen for this work. Based on the Euler-Bernoulli's beam theory and the magneto-thermoelastic theory of MMA, an integrated mathematical model of the beam embedded with MMA is developed. The attenuation in attainable strain of the actuator due to embedding is investigated for two cases viz, pure bending and combined extension-bending actuation. Simulation, using open-loop control scheme, shows that it is possible to attenuate the vibration by embedding MMA in the beam.

Investigation Of Active Vibration Damping Using Magnetostrictive Mini Actuator

J. Bi and M. Anjanappa

Presented at the 1994 SPIE Conference on Smart Structures and Materials, February, Orlando, FL. SPIE Paper No. 2190-82.

The feasibility of implementing embedded magnetostrictive mini actuators(MMA) for smart structure applications, such as vibration suppression of beams, is investigated in this paper. Based on the Euler-Bernoulli's beam theory and previously reported magneto- thermoelastic theory of MMA, an integrated mathematical model of the beam embedded with MMA is formulated. The effects of attenuation in attainable strain of the actuator due to embedding and vibration suppression effectiveness of MMA are theoretically examined for two cases viz, pure bending and combined extension-bending actuation. In addition, the determination for different forms of control schemes for MMA is investigated. Simulation, using open-loop control scheme, shows that it is possible to attenuate the vibration by embedding MMA in the beam. Further work on the further investigation of nonlinear close-loop control of MMA is in progress.

Dynamic Modelling of Smart Composite Beams

B. Bhattacharya, A.V. Krishnamurty, M. Anjanappa, and M.S. Bhat

Presented at the Conference on Developments in Advanced Composites and Structures, 17 September 1994, pp. 25-30, Hyderabad, India.

The structures capable of sensing vibration and autonomous self-actuation are defined as 'Smart/Intelligent Structure'. In this paper dynamic modelling os such a smart beam is presented. The beam is considered as a laminated composite structure having several continuously embedded layer of intelligent material. Terfenol-D-an alloy of Terbium, Dysprosium, and iron is chosen for actuation as it possess the magnetostrictive property of developing large strain under magnetic field. The ability of operating in a large bandwidth, high toughness, strength energy density are some of it's major features. The beam modelled is considered to be a unsymmetric laminate with specially orthotropic layers. The effect of finite thickness bonding layer is taken into account following a higher order shear deformation theory. Actuation/Control effort is described as induced strain and a new constitutive relationship is established. Variational techniques are used to develop the generalized equation of motion for the system.